

Viking gas chromatograph-mass spectrometer

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The Mars Viking gas chromatograph-mass spectrometer is described. The system is designed to determine the composition of the Martian atmosphere and detect and identify chemical compounds vaporized or pyrolyzed from the Martian soil. Construction details, performance data, data processing methods, and references to manufacturing and test procedures are also provided.

INTRODUCTION

Two Viking spacecrafts have successfully landed on Mars.¹⁻⁵ This paper gives construction details and performance data for the gas chromatograph-mass spectrometer (GCMS)⁶ on each lander. These instruments were designed to meet the scientific goals of the Viking program: specifically, to determine the composition of the atmosphere, with an emphasis placed on the detection of nitrogen, and to detect organic materials vaporized or pyrolyzed from the soil in the presence of water and carbon dioxide excesses, with an emphasis placed on detection of the types of compounds produced when terrestrial organic matter is heated.^{7,8}

It is impossible to present all of the technical details related to the GCMS in this report. The report is intended more as a guide to the technical information, which can be found through the references. The references have been separated into two categories: literature references to published information, and unpublished manufacturing information. It should be understood that reference to a specific manufacturer is not a recommendation, but rather a means of obtaining technical information which is public property. Further objectives of this paper are to provide information for

the reader to understand the way in which the GCMS functions in the lander, in terms of inputs and outputs, and the way in which the instrument performs the atmospheric and soil analysis experiments. Overall mission strategy for Viking has been reported.⁹

The paper begins at the lander level and proceeds through the GCMS system level to the subsystem level. A final section gives data processing methods and summarizes experiments performed during the mission. Because the report is so voluminous, and because it is desirable to provide access to the manufacturing procedures, each section or subsection is given as a functional description (how the part of the instrument being described performs a soil or atmospheric analysis), an operational description (how it works), and a manufacturing description (how it was made). Scientific reports on the results of the GCMS experiments on Mars have been given elsewhere.¹⁰⁻¹⁵

GCMS development philosophy

The design of the GCMS evolved over an eight year period (1967-1975). The overriding philosophy employed during this period was to verify the analytical capability of the instrument through testing. This approach uncovered many problems, among them the effluent

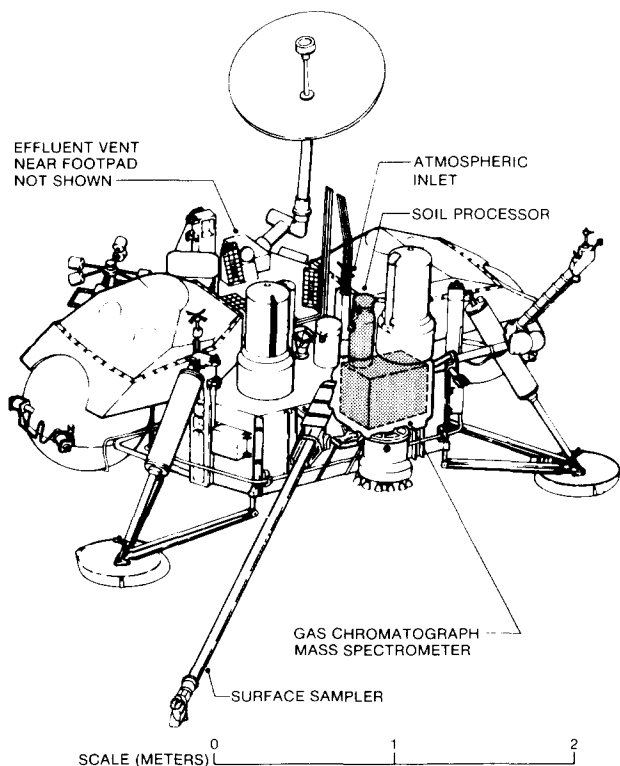


Fig. 1. Location of gas chromatograph mass spectrometer in Viking lander.

divider control system, the palladium alloy electrochemical separator, high-voltage corona, and catalytic reduction of organics in test soils by metal particles generated in the soil processor. These problems were solved by design refinement and subsequent test. The "proof-by-test" philosophy also led to an extensive number of tests of the actual flight hardware, an approach that involved some risk, and infrequently led to a great deal of rework. The test data generated in these tests permitted optimization of the hardware and of the operating conditions of the experiments prior to the first landing, i.e., the characteristics and behavior of the instrument were totally known prior to the landed phase of the mission.

I. LANDER/GCMS INTERFACES

The GCMS receives atmospheric and soil samples, power, commands, and heat from the lander. It returns data, heat, and vented gases. Figure 1 is a schematic diagram of the lander showing the locations of the atmospheric inlet, the soil acquisition system, the gas chromatograph effluent vent, and the GCMS soil processor.

A. Atmospheric sampling system

Atmosphere is admitted to the GCMS through a series of tubes atop the lander, as is shown in a layout view in Fig. 2.¹⁶ These tubes are nominally 8.5 mm i.d. The ends of the tubes which sample the atmosphere are pointed in opposite directions and are cut at opposing 45° angles. This configuration was chosen to stimulate the flow of atmospheric gases through the system under

the influence of the Martian wind.¹⁷ These tubes are connected to the atmospheric dust trap, a split box $30 \times 7 \times 4$ cm. The dust trap prevents windblown particles from reaching and therefore clogging the remainder of the atmospheric inlet system. Out of the dust trap extend two tubes which penetrate the top surfaces of the lander and extend to a T connection approximately 6 cm from the GCMS instrument. A fitting at the instrument permits connection and disconnection of the instrument from the lander. Total length of the tubes (from sampling point to instrument to sampling point) is 2.25 m. Under stagnant atmospheric conditions, the composition of a sample at the instrument will reflect a change in the atmosphere at the sampling point within 1 h.¹⁷

B. Soil sampling system

Soil samples are collected by a small scoop attached to a furlable boom.¹⁸ The scoop can be targeted to any point within the sample area upon command by the lander computer. A backhoe on the underside of the scoop can be used to scrape away surface material so that underlying soil can be sampled. In operation, the lid on the scoop is opened, the scoop is lowered to the surface and driven into the soil by extending the boom. The lid is then closed, and the scoop retracted and repositioned over the soil processor. The scoop is

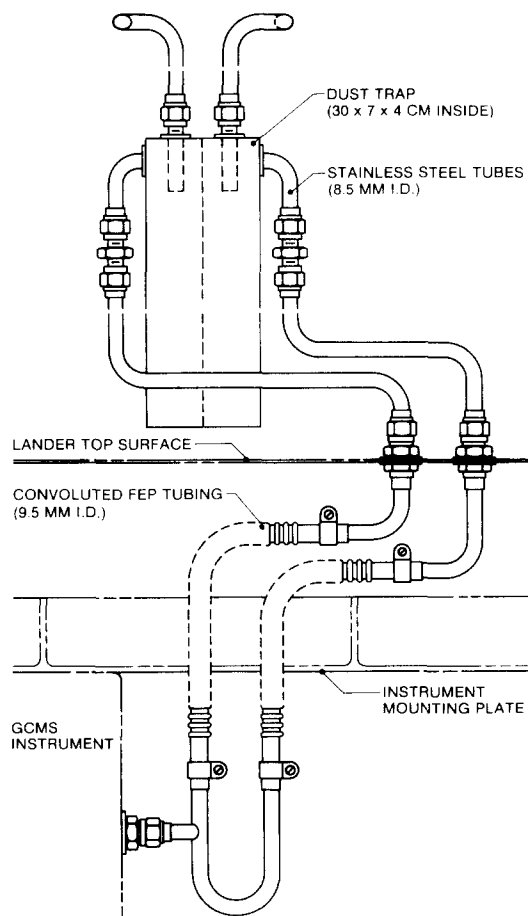


Fig. 2. Layout diagram of Viking lander atmospheric inlet system.

then inverted and shaken. Soil falls through a mesh with 2 mm openings in the top of the scoop and in the top of the soil processor.

The soil processor consists of subassemblies which grind the soil, measure it, and deliver it to the GCMS soil loader (described in detail in a later section). A diagram of the soil processor is shown in Fig. 3.¹⁹ Soil particles up to 2 mm diameter fall through the screen which covers the top of the mechanism and accumulate in the soil funnel. They are ground to $<600\text{ }\mu\text{m}$ by the action of an auger against a conical surface. Simultaneously, a rod through the funnel stirs the soil and taps the bottom of the screen on top of the mechanism. This action causes the soil to drop through the funnel and be ground. After grinding, soil particles less than $300\text{ }\mu\text{m}$ diameter are forced through $300\text{-}\mu\text{m}$ -diam holes into a 1-cm^3 cavity. This cavity is located in a movable metal block which contains redundant thermal conductivity sensors to determine when it is full. When a "level full" is obtained, it is used to stop the grinding operation. The cavity is then positioned over the GCMS delivery tube and sample is delivered by gravity to the GCMS soil funnel. When the cavity is empty, as determined by the sensor, the GCMS sequence is started. Failure of the sampler to deliver soil to the processor, or failure to obtain "level full" or "level empty" signals results in an abort of the GCMS

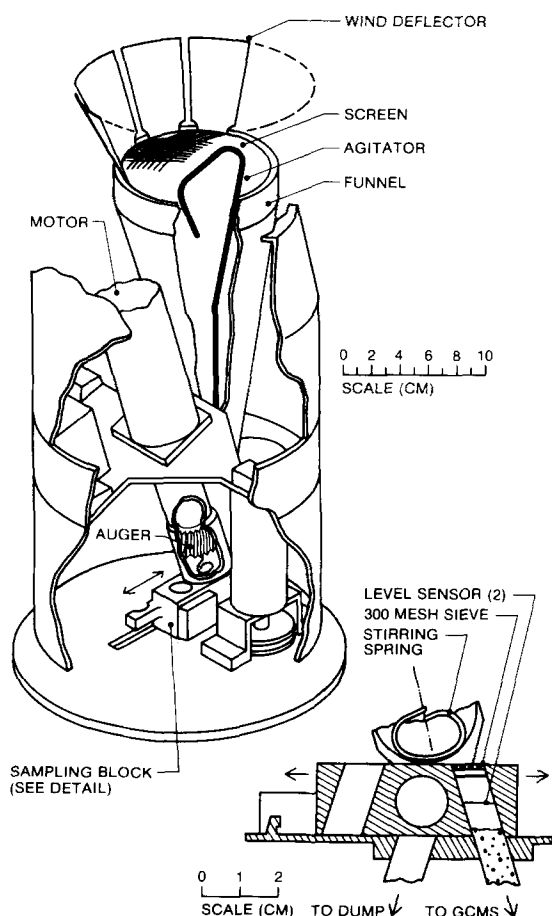


FIG. 3. Gas chromatograph mass spectrometer soil processor.

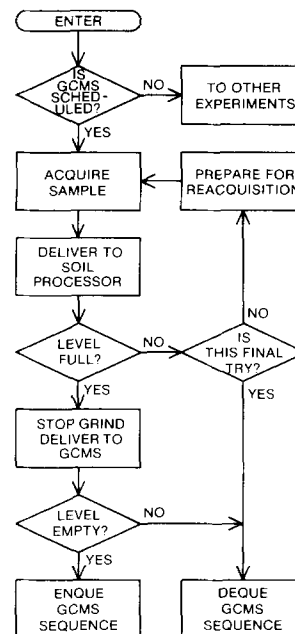


FIG. 4. Soil acquisition logic.

analysis sequence, which must then be overridden by ground command or another acquisition attempt must be made. A simplified diagram of the interactive logic which controls the total soil acquisition sequence is shown in Fig. 4.²⁰

C. Instrument power

Power within the lander is generated by a pair of radioisotope thermoelectric generators and is stored in four nickel-cadmium batteries, which are alternately charged and utilized.²¹ Power is provided to the GCMS in several forms. A 30-V dc $\pm 20\%$ high-current line is used to provide the main operating power to the instrument. This power is normally off and is turned on only when a sequence is being performed. During operation, power consumption by the GCMS ranges between 25 and 140 W. The ion pump derives its power from the lander critical loads bus and is powered continuously. It consumes approximately 0.25 W when quiescent. An emergency power pulse²² is provided to close certain GCMS valves in the event of a power failure to preclude loss of mass spectrometer vacuum and loss of consumables.

D. Commands

Commands to the GCMS are transmitted to the lander from earth via space network stations at Goldstone, CA, Canberra, Australia, and Madrid, Spain.²³ During the primary mission, commands are transmitted every other Martian day to one lander only (the one experiencing high activity). The commands are stored in the lander computer and are transferred to the GCMS computer when a GCMS sequence is to be performed. Table I gives an example of the commands and timing associated with an organic and an atmospheric analysis sequence as controlled by the lander. In order to act upon a

TABLE 1. Lander controlled atmospheric and organic analysis sequences.

Atmospheric analysis (with CO/CO ₂ and H ₂ O removal).	
Command	Purpose
1	Open atmospheric inlet valve (V9).
Wait 3600 s	Permit equilibration with atmosphere.
2	Close inlet valve, open CO/CO ₂ absorber valve (V10).
Wait 2700 s	Permit removal of CO and CO ₂ .
3	Close V10, open H ₂ O absorber valve (V11).
Wait 900 s	Permit removal of H ₂ O.
4	Close V11, analyze sample at low ionizing voltage.
5	Analyze sample at high ionizing voltage.
Soil load and analysis.	
Command	Purpose
1	Preheat sample oven.
2	Unseal from previous oven.
3	Index oven to Load position.
Wait 1–2 h	Acquire sample, grind, and deliver to soil funnel.
4	Load sample into oven.
5	Index oven to analyze position.
6	Seal sample oven.
Wait 1–12 h	Take pictures of sampling area, cool lander.
7	Analyze soil at temperature T1.
Wait 2–10 sols	Update next analysis based on T1 analysis data.
8	Analyze soil at temperature T2.

command, the instrument must be “powered-on” and in the “standby” mode. It will not accept a command if one is in the process of being executed. The command itself is a 48-bit binary word which determines the specific sequence and operating parameters for the instrument.²⁴ After the command is entered in the GCMS computer, a “command enable” is sent from the lander computer to the GCMS computer and command execution begins.

E. Data

Data are returned to the lander by the GCMS computer and are collected in the data storage memory, or sent directly to the lander tape recorder. The data storage memory has a capacity of 196 kilobits. When full, or upon command, this memory is dumped to the tape recorder. The tape recorder has four tracks with a capacity of approximately 10 megabits per track. Two to three tracks of data are relayed to Earth through an orbiter each Martian day during the primary mission.²⁴

F. Thermal

Heat is transferred between the GCMS and the lander through the instrument mounting surface. The nominal operating temperature range of the instrument is -5° to $+40^{\circ}\text{C}$. During periods of instrument operation, heat is transferred to the lander from the GCMS, whereas, during quiescent periods the instrument tracks the lander internal temperature.²⁴

G. Vented gases

Hydrogen and gas chromatographic effluent gases are vented through the lander and exit near one of the

footpads. This location was chosen to minimize interaction between this vent and the atmospheric inlet system.

II. INSTRUMENT SYSTEMS

A. Mechanical structure

In order to withstand launch and descent vibration and landing shock,²⁴ the GCMS structure is separated into the major elements shown in Fig. 5. The main structure is comprised of three nickel-plated thoriated magnesium alloy trays 28×38 cm by 5–8 cm thick. These trays are held together by 12 titanium alloy structural bolts. Electrical connectors and cables carry signals between the trays, and the mating surfaces and bolts conduct heat throughout the structure. The “sensor” tray²⁵ holds the major functional assemblies of the GCMS and the mass spectrometer electronics. The “electronics” tray²⁶ holds the control electronics for all system elements except the mass spectrometer. The “data system” tray²⁷ holds the GCMS computer, which is comprised of the sequence controller, effluent divider controller, column temperature programmer, and data digitization and output control electronics.

Minor structural elements include the housing for

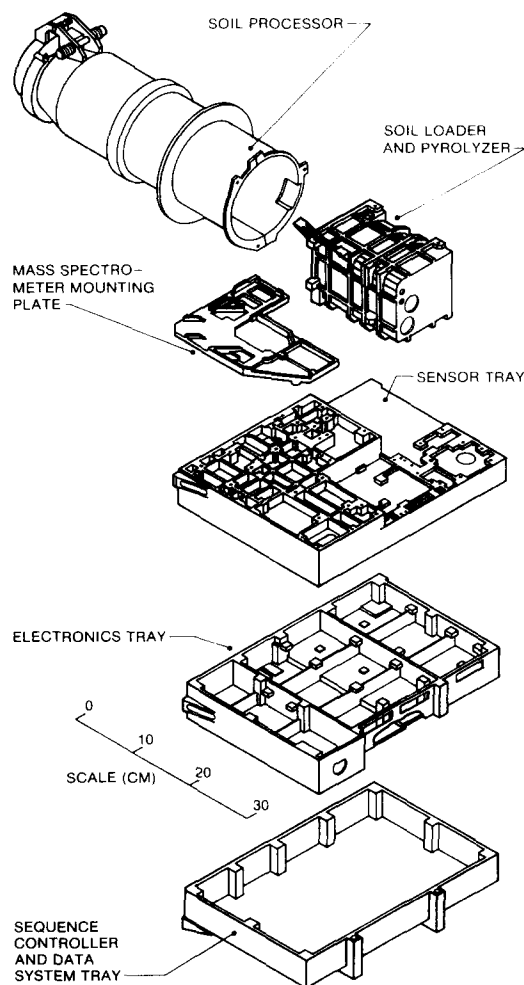


FIG. 5. Gas chromatograph mass spectrometer structural tray system.

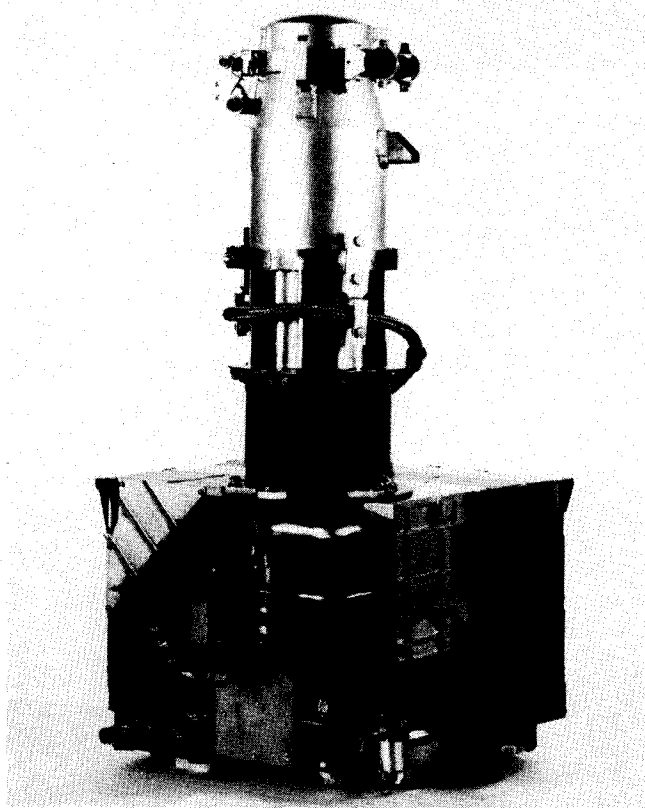


FIG. 6. Viking gas chromatograph mass spectrometer.

the GCMS soil loader and pyrolyzer assembly²⁸ which ties the soil processor to the tray system, and the mass spectrometer mounting plate, a rigid sculptured piece of stainless steel which maintains optical alignment of the mass spectrometer.²⁹ This plate is isolated from the sensor tray by use of spring steel (Belleville) washers, and therefore decouples the mass spectrometer from the thermal expansion and contraction of the magnesium alloy tray. Figure 6 is a photograph of the instrument which shows the total integrated structure.

The instrument is mounted inside the lander and is suspended from the lander equipment mounting plate

using 17 bolts.²⁴ The soil processor protrudes from the top lander surface. Total weight of the instrument, including the soil processor, is 25 kg.

B. Power regulators

A self-contained power conditioning system is used to convert unregulated 30-V lander power to regulated power to the instrument. A simplified schematic diagram of the converter, along with the output voltages it provides, is shown in Fig. 7.³⁰

C. GCMS system control computer

The computer can be separated functionally into two parts: the command processor and sequence controller,³¹ and the data digitizer and output control logic.³² Redundant clocks provide timing signals to the computer; a failure in the primary clock system causes automatic switching to the backup clock. A block diagram of the computer is shown in Fig. 8. Upon "power-on" of the instrument, the computer automatically enters an "initialization" sequence which closes certain valves and clears the command and data registers. In addition, if a voltage transient occurs during a sequence, the computer automatically terminates that sequence, reenters the initialization sequence, and then returns to the "stand-by" mode to await further command from the lander computer.²⁴

The command processor accepts commands from the lander computer, selects the appropriate instrument operating parameters, and initiates the execution of the specified sequence when the command enable signal is received. The sequence controller issues control instructions at predetermined time intervals during the sequence.³³ A partial list of sequences, subroutines, and parameters is given in Table II. The individual control instructions and time delays are stored in a 512-word (12-bit word) Programmable Read Only Memory (PROM), which is programmed during construction of the instrument. An example of an atmospheric analysis sequence is shown in Table III.

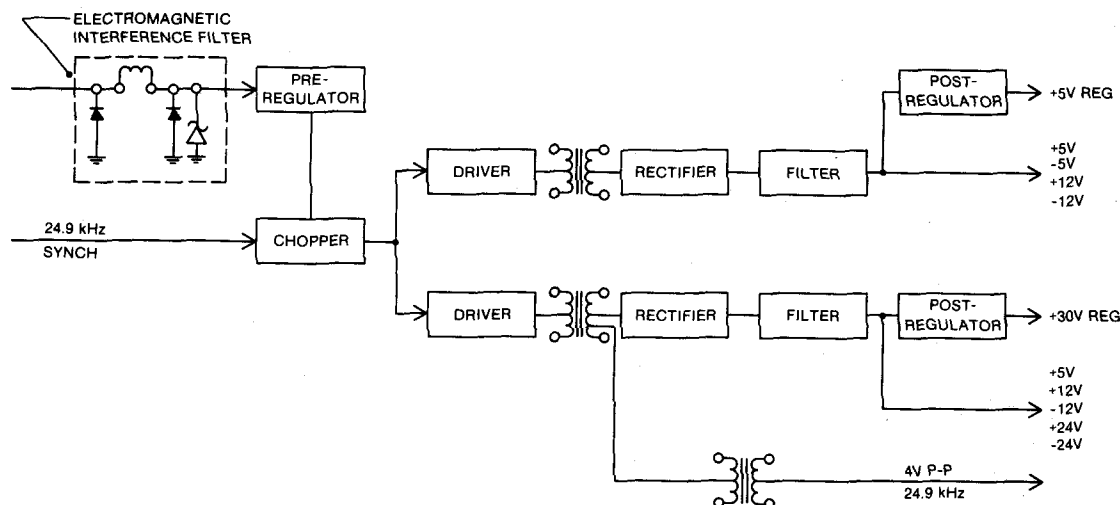


FIG. 7. GCMS power regulation schematic diagram.

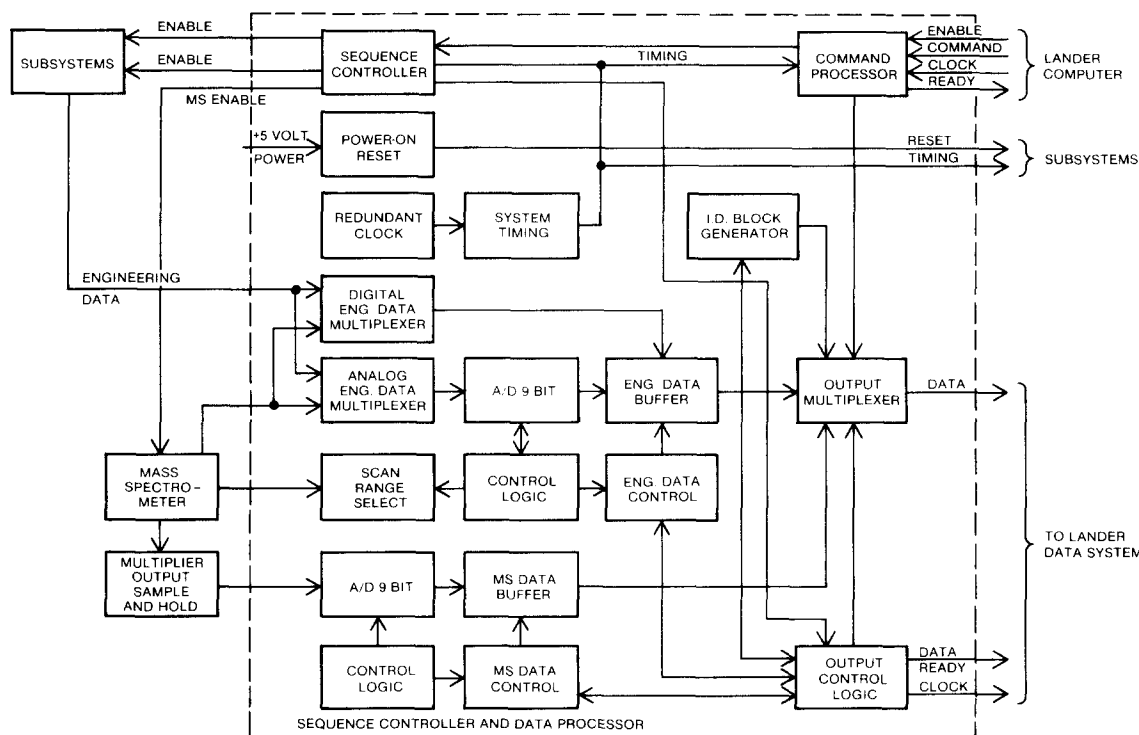


FIG. 8. Block diagram of GCMS computer.

Forty-eight separate and commandable sequences are available with each sequence employing various combinations of 76 instructions and 34 delay times.

The data digitizer and output control logic section of the computer accepts signals from the operating elements of the GCMS and prepares those signals for

output to the lander. The data are classified into two categories: engineering, and mass spectrometer output. A list of parameters measured in the output data format is given in Table IV. The mass spectrometer output data are the output of the electron multiplier (resolved ion current). The instrument normally operates in two data output modes: engineering data only, or engineering plus MS output. Included in the data are a GCMS identifier, a data block count, and a scan frame count,^{24,34} which assist in the separation and recovery of GCMS data from the total data stream.

III. INSTRUMENT SUBSYSTEM DETAILS

A. Introduction

The GCMS instrument can best be understood through the use of the schematic flow diagram in Fig. 9. Atmospheric samples are admitted to a 10 cm³ chamber through valve V9. These samples can then be analyzed

TABLE II. Partial list of GCMS control sequences, subroutines, and parameters.

Sequence	Purpose
Power-on-reset	Reset valves, clear registers.
Vent-in-flight	Vent GC to space during cruise.
Open atmospheric inlet valve	Admit sample to instrument.
Bakeout-in-flight	Outgas terrestrial contaminants.
Condition GC column	Purge contaminants from column.
Atmospheric analysis	Analyze sample.
Preheat sample oven	Outgas contaminants.
Load sample oven	Fill oven with soil.
Dump excess sample	Self-explanatory.
Organic analysis	Analyze soil sample.
Subroutine	
Carriage/clamp position test	Verify oven and clamp position.
ED/MSO mode select	Specify mode of effluent splitter.
Organic analysis	Column isothermal holds and ramp.
Parameter	
Oven seal clamp position	Verify clamp open or closed.
Oven carriage position	Verify oven position.
Oven carriage transfer position	Specify destination when moved.
Electron multiplier gain	Select desired gain (3 settings).
Filament	Select filament (of 2).
Ion beam voltage	Select 45 or 70 eV.
Oven	Select oven 1 thru 3.
Oven temperature	Select 50°, 200°, 350°, 500°C.
Data rate	Select output data rate.

TABLE III. Atmospheric analysis sequence.

Enter
Wait 16 scan periods (163.804 s)
Atmospheric analysis on
Mass spectrometer on
Wait 248.348 s
Output MS data on
Wait 3 scan periods (31.704 s)
Output MS data off
Open valve V12
Wait 303.830 s
Output MS data on
Wait 4 scan periods (42.372 s)
Close valve V12
Return to standby mode

TABLE IV. GCMS output measurements.

Parameter	Measurement frequency
Hydrogen tank pressure	Every 16 scans (163.808 s)
Sample inlet temperature	Every 16 scans (163.808 s)
Thermal zone temperature	Every 16 scans (163.808 s)
Oven outlet line temperature	Every 16 scans (163.808 s)
Column temperature	Every 16 scans (163.808 s)
Separator current	Every 16 scans (163.808 s)
Ion source temperature	Every 16 scans (163.808 s)
Sensor tray temperature	Every 16 scans (163.808 s)
Ion pump high voltage	Every 16 scans (163.808 s)
Multiplier voltage	Every 16 scans (163.808 s)
A/D converter calibrate	Every 16 scans (163.808 s)
Valve status (V0, V1, V2, V3, V7, V9, V10, V11, V12, V13)	Every 16 scans (163.808 s)
Data system clock	Every 16 scans (163.808 s)
Oven carriage/clamp position	Every 16 scans (163.808 s)
Ion pump current discriminators	Every 16 scans (163.808 s)
Oven time to temperature	Every 16 scans (163.808 s)
Log ion pump current	Every scan (10.238 s)
Valve status (V4, V4A, V5, V6)	Every scan (10.238 s)
Log total ion current	Eight times per scan (~1.3 s)
Scan voltage	Eight times per scan (~1.3 s)
Log resolved ion current	3840 times per scan (~2.5 ms)

directly by the mass spectrometer by opening valve V12 and permitting flow through the molecular leak into the ion source. The samples can also be analyzed after removal of carbon monoxide, carbon dioxide, and water through the use of chemical scrubbers.

Soil samples are delivered from the soil processor to the soil loader and pyrolyzer assembly and loaded into the soil ovens. After an oven has been loaded, it is positioned between circular knife edges which are then clamped to seal the oven in the analyze position. During an analysis, either ^{13}C tagged carbon dioxide is used to push the vapors generated in the oven into the gas chromatograph, or the vapors in the oven are permitted to expand and push themselves into the chromatograph. Hydrogen is used to elute the vapors from the column. Downstream of the column is a five-stage effluent splitter which is controlled by the mass spectrometer ion pump in order to prevent pump overload and maintain sample concentrations within the analyzing range of the mass spectrometer. Sample enters the mass spectrometer through a palladium alloy separator

which removes the hydrogen carrier gas. Valve V7 is used to protect the mass spectrometer from gross overloads and is closed when the system is not in use. Figure 10 shows the way in which the various subsystems are mounted on the sensor tray.

B. Mass spectrometer (MS)

The spectrometer³⁵ is a Nier-Johnson, 90° electric sector, 90° magnetic sector, electrically scanned instrument, with optical dimensions shown in Fig. 11.³⁶ It employs a differentially pumped, dual filament, electron bombardment ion source with selectable ionizing energies of 45 or 70 eV. The ion source is operated at lander ambient temperature when atmospheric samples are analyzed, and heated to 200–260°C when soil samples are analyzed. The accelerating potentials are scanned exponentially downward from 2350 to 125 V in 9.91 s. The system has a mass voltage product of 28 000 which produces a mass range of approximately 12–215 amu. The sector plate voltages operate at approximately 6.7% of the scan voltage. A collector is employed at the source exit to measure total ion current. An electrometer converts the logarithm of the total ion current over the range 3.2×10^{-13} to 3.2×10^{-8} A to a 0–5 V linear signal.³⁷ Subsequently, the 0–5 V signal is converted to 9 bits by the GCMS computer. This signal is sampled eight times per scan.

The magnetic sector utilizes an Alnico V magnet with type 410 magnetic stainless steel pole pieces which are welded into the vacuum envelope. The magnet gap is 2.54 mm. During construction of the instrument the magnet is charged to saturation, then discharged to a field strength of 6326 G. A sputter ion pump with an effective pumping speed for most gases of 500 cm³/s utilizes the same magnet as the magnetic sector. The pump is operated at 4–5 kV over a current range of 0.06–4000 μA . The power supply reduces the ion pump voltage from full to zero volts over the current range of 2–4 mA. The logarithm of the pump current over the range 0.06–5900 μA is converted to a 0–5 V linear signal which is then digitized to 9 bits. Pump current is sampled once per scan.

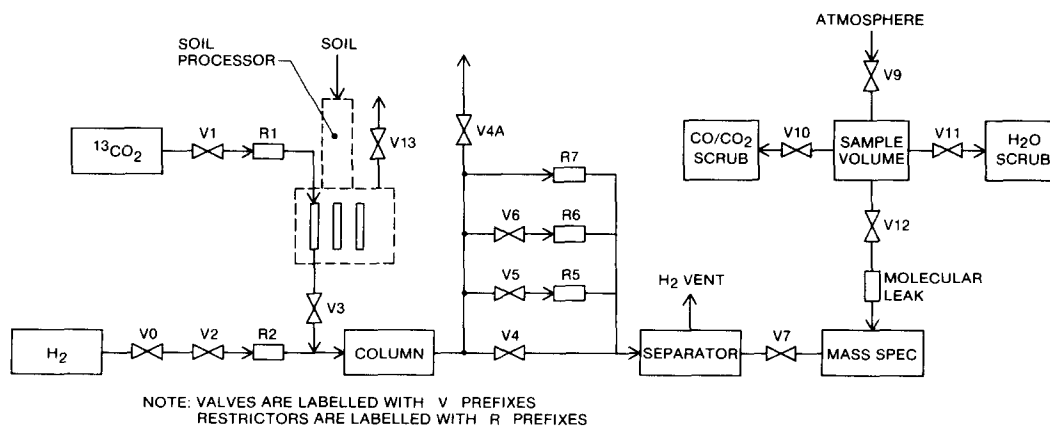


FIG. 9. Simplified flow diagram of GCMS.

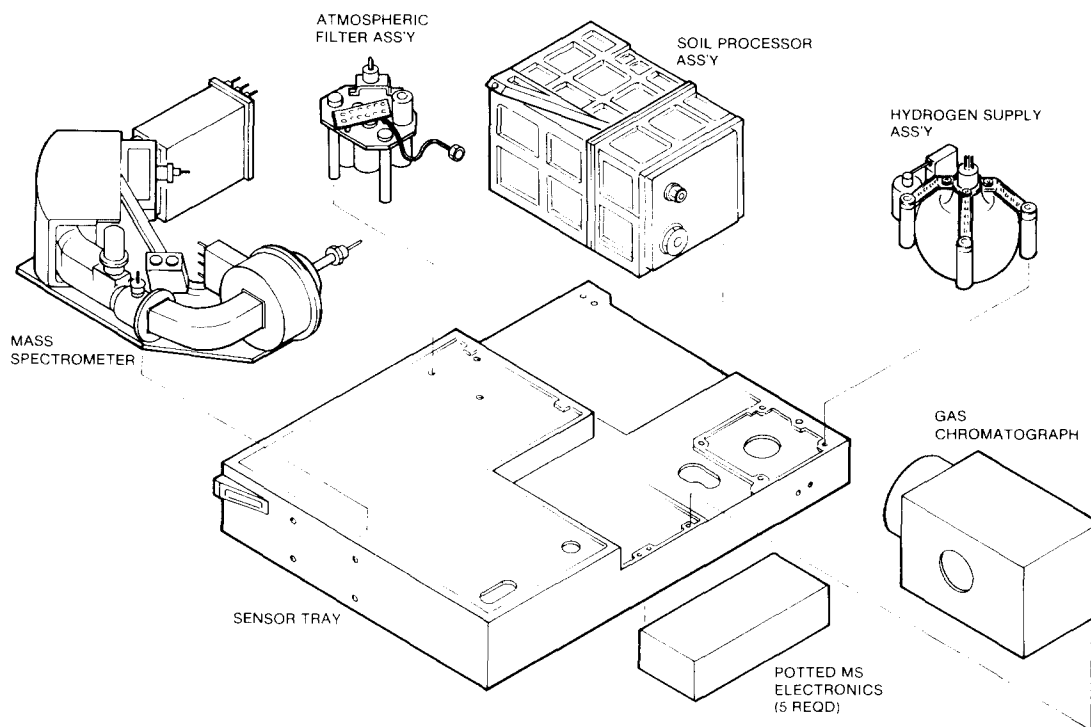


FIG. 10. Mechanical arrangement of subassemblies on sensor tray.

The MS employs a 0.051-mm image slit with a radius of curvature of 2.3 cm. The electron multiplier is a 12-stage Venetian blind device employing beryllium-copper dynodes. It is operated at potentials of 1200–2250 V over an output current range of 10^{-13} – 10^{-6} A. The logarithm of the output current is converted to a 0–5 V linear signal which is then digitized to 9 bits. The signal is sampled 3840 times per scan (once every 2.58 ms). A calibration curve for the electron multiplier output signal processing system (electrometer,³⁸), sample-and-hold,³⁹ and A/D converter⁴⁰ is shown in Fig. 12.

C. Details of the ion source and electric and magnetic sectors

Ion source details are shown in Fig. 13.⁴¹ Electrons are generated at either of two U-shaped filaments, are accelerated to a potential of 300 V, and are focused on the ion box entrance aperture where they are decelerated to a potential of 45 or 70 V. The detailed cross-sectional view in Fig. 13 shows the alignment between the filaments, entrance aperture, and ionization region of the source. The ionizing region lies along the axis of a tubular magnet which has a slot cut axially on one side for extraction of ions. A curved repeller which is designed to follow the electric field lines in the ionizing region is fitted into the magnet. The ions are accelerated through a "saddle" lens and focused on the source exit slit by a split lens pair. The total ion current monitor collects stopped ions impinging on the source exit. The filament assembly is insulated with ruby washers while the ion focusing assembly is insulated with beryllium oxide rings. All electrical connections are spot-welded to the source elements on one end and to pins on a hermetic feedthrough on the other end.

The feedthrough⁴² contains 23 pins and is specially designed to eliminate corona at Martian ambient pressures. Thermistors, imbedded in the "block" which surrounds the ionizing region, are used to control the heater which is formed by electrodeposition of tungsten on a beryllium oxide ring adjacent to the total ion current monitor.⁴³ Atmospheric samples enter the source through the molecular leak⁴⁴ while samples from the chromatograph bypass the leak and enter the source directly.⁴⁵ Conductance of the molecular leak is instrument dependent and ranges between 1.4 and 3.3×10^{-4} cm³/s. Differences in molecular leak conductance are offset by adjustment of electron multiplier gain. The electron entrance aperture and the ion exit slit form the only two gas paths out of the source into the analyzer. This design results in a differential pressure ratio of about 10 between the ion source and the analyzer. Response of the source to nearly all fixed gases is linear to a pressure of 7×10^{-5} millibars. Source sensitivity for nitrogen is approximately 3×10^{-6} A/millibar.

The electrostatic analyzer is shown in cross section in the detail in Fig. 11.⁴⁶ It is made by assembling eight circular stainless steel rings. The sector plates are held in position by ruby dowel pins and ruby washers. Fabrication of the electrostatic sector consists of clamping the eight rings together with the ruby washers and dowels in place and then electron beam welding all of the seams to form a vacuum-tight assembly. The ring assembly is then cut into three pieces which will yield three electrostatic sector assemblies after final machining. This method of manufacture produces precisely aligned sector plates (misalignment throughout is less than 0.025 mm) at minimum weight and volume.

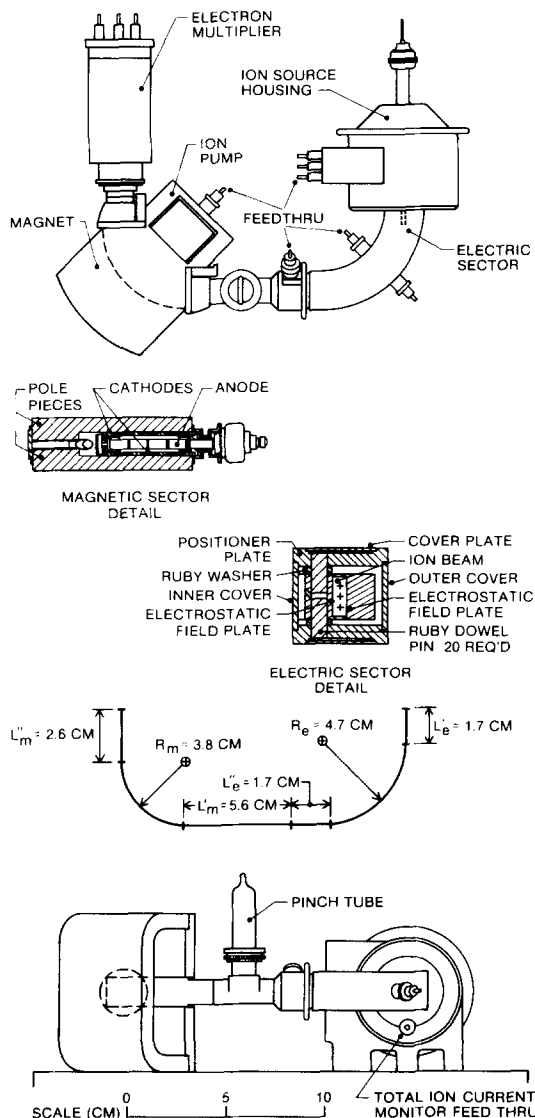


Fig. 11. Double-focusing mass spectrometer.

The electrostatic sector is electron beam welded to the ion source housing and to an adapter which is in turn tungsten-inert gas welded to the "drift tube" between the sectors. The drift tube section of the analyzer⁴⁷ houses a slit which is used during buildup of the instrument for the purpose of performance assessment of the ion source and electrostatic sector combination. This slit is grounded thereafter. Attached to the drift tube is a soft copper tube which is used during assembly, bakeout, and test for maintenance of vacuum within the analyzer by an auxiliary vacuum system. This tube is pinched off prior to flight acceptance testing and delivery.⁴⁸

The magnetic sector and ion pump assembly⁴⁹ is also shown in cross section in Fig. 11. Unique to this design is the use of the magnet pole pieces as elements of the vacuum housing. Significant weight savings result. The pole pieces are held parallel during manufacture by clamping them to an aluminum block and welding them into a nonmagnetic housing. The aluminum block is then removed. The ion pump is comprised of two

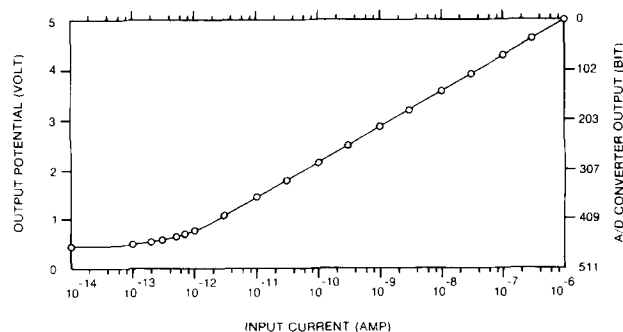


Fig. 12. Resolved ion current logarithmic electrometer output signal calibration.

titanium cathodes and a stainless steel anode. The cathodes are slotted to promote ion burial. Effective pumping area is 6.3 cm^2 . The cathodes operate at ground potential whereas the anode operates nominally at 4 kV. A magnetic field of approximately 2100 G in the pump region is supplied by the same magnet as is used for the magnetic sector.⁵⁰

The image slit⁵¹ and electron multiplier⁵² are housed in stainless steel.⁵³ A six-pin feedthrough⁵⁴ is used to

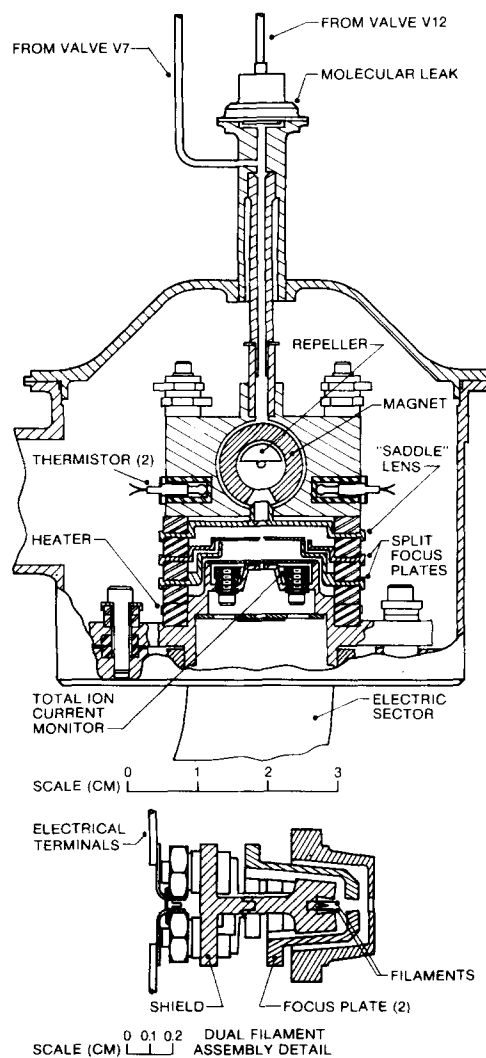


Fig. 13. Ion source.

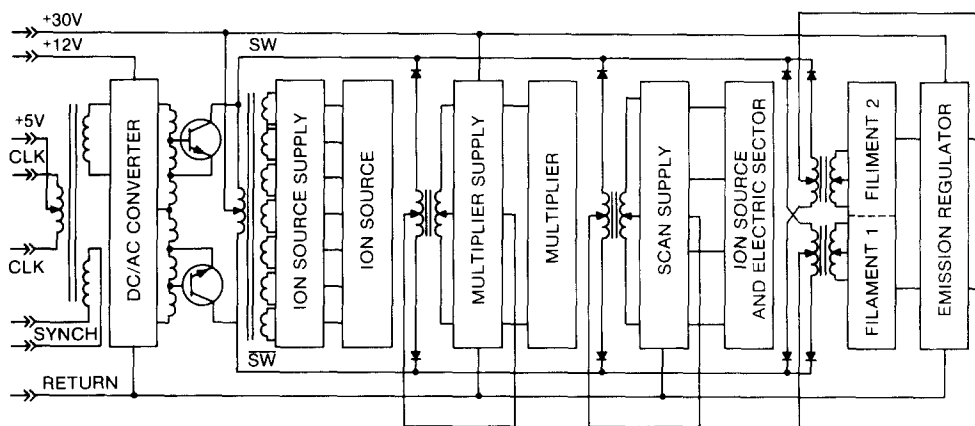


FIG. 14. Mass spectrometer scan electronics simplified block diagram.

supply voltage to the multiplier and to feed the output current through the vacuum envelope.

Extensive alignment of the analyzer is required during manufacture. Flexibility in final tuning of the system is maintained by permitting degrees of freedom in selecting source and electrostatic sector potentials, and magnet and image slit positioning. These variables are fixed only after their respective optimum values have been determined.

D. Mass spectrometer electronics⁵⁵

Two independent power supply systems provide the necessary potentials for operation of the mass spectrometer. The scan, filament, ion source, and electron multiplier (EMT) voltages are drawn from the GCMS power converter, whereas the ion pump high-voltage supply gets its power directly from the lander critical loads bus. Power supply efficiency was an important consideration in the design of both of these systems. In the case of the scan, filament, ion source, and EMT voltages, the requirement of high efficiency led to the bus configured dc/dc converter system shown in Fig. 14. In this system, a dc/ac converter⁵⁶ develops "switch" (SW) and "switch bar" ($\overline{\text{SW}}$) signals by use of a center-tapped driver transformer. These two signals are then bussed to four other transformers:

(1) The EMT transformer drives a standard Cockcroft-Walton supply and provides voltages of 1200–2250 to the EMT.⁵⁷ Three fixed voltages are selectable⁵⁸ and are preset during manufacture to match the EMT gain to the MS dynamic range for atmospheric measurements. Supply regulation is achieved by feedback of the dc voltage level at the center tap of the high-voltage transformer. A monitor signal is fed to the data system.⁵⁹

(2) The scan supply⁶⁰ is regulated in a manner similar to the EMT supply except that an exponentially decaying reference voltage (internal to the scan supply) drives the scan voltages. In this case, the reference voltage is applied to the center tap of the transformer to provide the desired exponentially decaying high voltages. A monitor signal from the scan supply is scaled into four voltage ranges. Range and voltage information is then digitized into the output data stream.

(3) The filament and emission regulator supplies⁶¹ operate somewhat differently from those described above, in that a pulse width modulated signal is applied to the center tap of the driver transformer. This method was chosen because the filament supplies are higher power devices than the EMT and scan supplies.

(4) The fourth transformer drives a supply which provides the necessary ion source potentials.⁶²

The ion source and filament supplies are referenced to the scan supply. All voltages track within 0.1% during a scan. Noise on all voltages is held to less than 1.5%. Sensitivity and resolution loss occurs if these tolerances are exceeded. Scan initiation is controlled by the data system and occurs every 10.24 s. Scan reset (from low to high voltage) takes place during a 0.33 s period at the end of each scan.

The ion pump high-voltage supply⁶³ is shown in block diagram form in Fig. 15. This circuit is regulated against line voltage changes by pulse rate control and regulated against load voltage changes by pulse amplitude control. Ion pump voltage and current monitor signals⁶⁴ are fed to the data system and lander. A logarithmic electrometer transduces pump current to discrete discriminator signals (described in detail in Sec. III L) and to the data system.⁶⁵

The ion source temperature controller⁶⁶ and a noise filter for electric sector potentials⁶⁷ make up the remainder of the MS electronics.

All high-voltage electronics assemblies are potted in silicone polymer to diminish the likelihood of corona.⁶⁸ Similarly, connections at the mass spectrometer, which proved to be most susceptible to corona, are potted in polyurethane filled with aluminum oxide particles.⁶⁹ The potting of these components was found to be of critical importance in producing an instrument which was to withstand the corona environment at the Martian surface.

E. Atmospheric inlet

A cross-sectional view of the atmospheric inlet assembly is shown in Fig. 16.⁷⁰ Valves V9, V10, and V11⁷¹ are "high-conductance" valves, and are attached to the sampling volume. High conductance is required

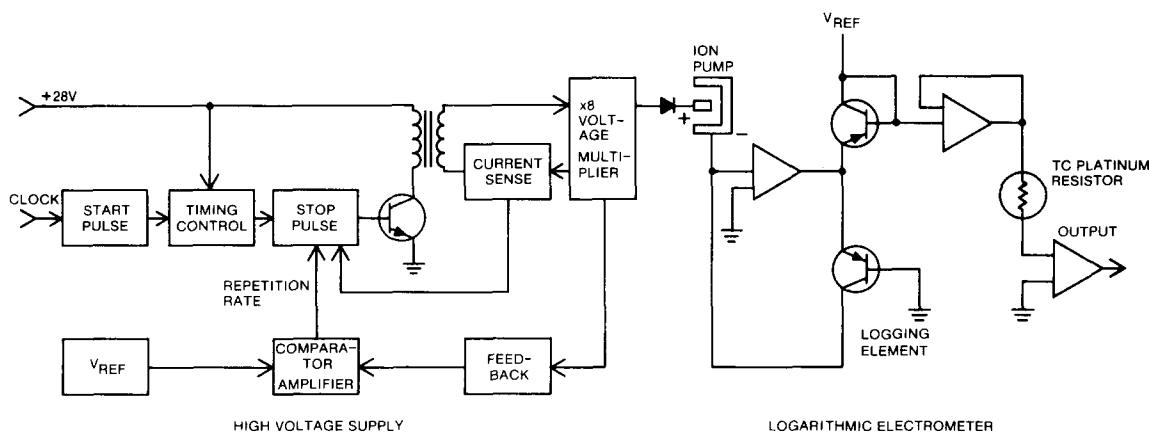


FIG. 15. Ion pump high-voltage supply/electrometer block diagram.

by the short diffusion times imposed upon the system. For example, the time required for the sampling volume to reach diffusion equilibrium with the Martian atmosphere (outside the lander) is less than 1 h. Had the time been much longer, fewer atmospheric samples could have been acquired in a given day.

In order to detect nitrogen, chemical absorbers^{72,73} are provided to remove carbon monoxide (CO) and carbon dioxide (CO₂), which have interfering mass spectral peaks with nitrogen at *m/e* 28 and 14. Carbon dioxide removal has the further benefit of increasing the partial pressure of trace constituents in the "enrichment" mode (described later). Carbon monoxide is oxidized to CO₂ by silver oxide (Ag₂O), and total CO₂ is removed by lithium hydroxide (LiOH). Water is generated in the process and is subsequently removed by magnesium perchlorate [Mg(ClO₄)₂]. The absorbents could not be combined because the Mg(ClO₄)₂ totally dehydrates the LiOH, and a small amount of H₂O is necessary to catalyze the CO₂ removal by LiOH. Heaters are attached to the equilibration volume and the CO/CO₂ absorber capsule to prevent ice from clogging the screens which support the chemicals, and to increase the rate of reaction of CO with Ag₂O. The heaters are energized when valve V10 opens.⁷⁴ A bimetallic thermostat is used to maintain capsule temperature at 25°–35°C. The time required for removal of CO₂ and CO to less than 0.02% and 1% of their initial levels, respectively, is 45 min; the time required for removal of the resulting H₂O to 1% of its initial level is 15 min. Enough chemicals are provided for 300 removal cycles at Martian pressure.

Referring to Fig. 16, the CO/CO₂ absorber contains 160 mg of LiOH and approximately 50 mg of Ag₂O, which are held in an annular space inside the capsule. Similarly, the H₂O absorber contains 90 mg of Mg(ClO₄)₂. The LiOH is prepared⁷⁵ by pressing the monohydrate form into pellets at 1.38 kilobars, breaking the pellets into granules, sieving the granules to 45–50 mesh, and then baking the sieved granules at 150°C and <1 millibar for 4 h. The silver oxide is prepared⁷⁶ by precipitation from AgNO₃ solution using 4*N* NaOH. The particles are washed, dried for 4 h at 85°C and 1 millibar,

and then sieved to 40–60 mesh. The magnesium perchlorate is baked at 240°C and 1 millibar for 4 h and sieved to 40–60 mesh. After baking, all operations using the chemicals are performed in a dry box under nitrogen.⁷⁷

Using the system described above, a limit of detection for nitrogen of 100 ppm at a signal-to-background ratio of four was attained. This capability proved unnecessary, for nitrogen was detected at the 3% level by the Upper Atmosphere Mass Spectrometer upon entry of the spacecraft into the Martian atmosphere.⁷⁸ However, the CO/CO₂ removal system proved invaluable for detecting trace gases in the "enrichment" mode. In this mode, atmosphere is admitted to the sampling volume and CO, CO₂, and H₂O are removed. Removal of these gases creates a partial vacuum in the sample volume. Rapidly opening and closing valve V9 (total time open is 4 s) permits more atmosphere to enter the volume, yet prevents diffusive escape of the gases inside. Repeating this process 15–20 times produces an increase in the partial pressures of the trace gases within the sample volume. The result is a lower detection limit for the system for trace constituents which have no interfering mass spectral peaks. The detection of krypton and xenon was made possible by this enrichment process.¹³

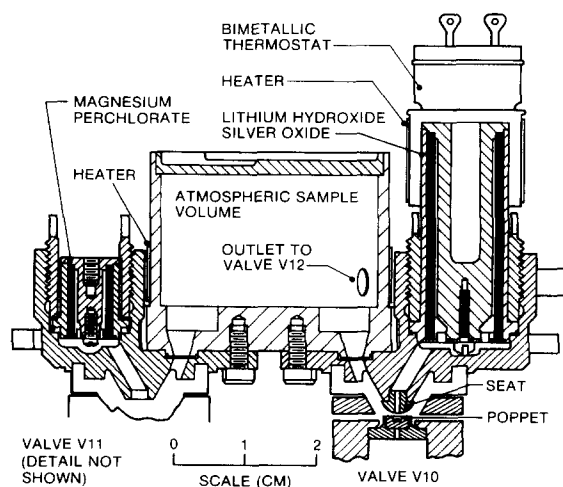


FIG. 16. Cross-sectional view of atmospheric inlet system.

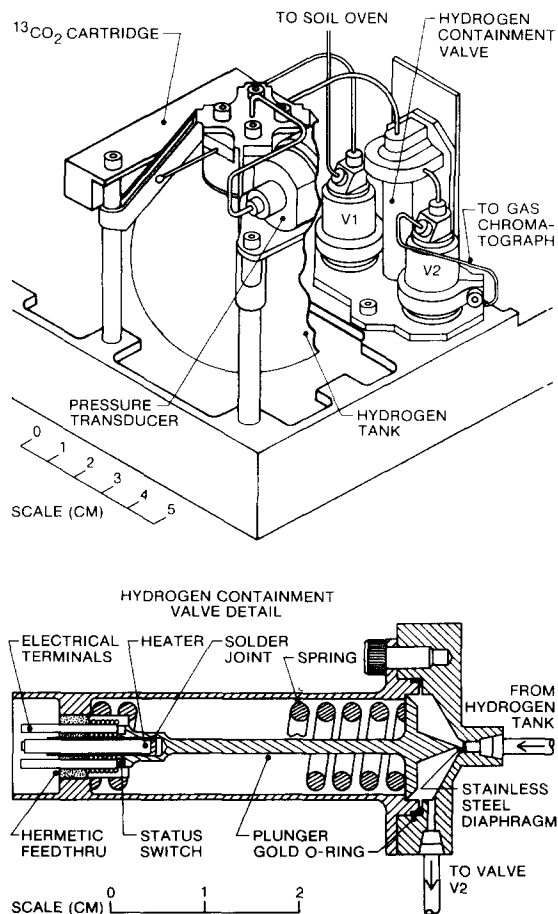


FIG. 17. Carrier gas supply system.

F. Carrier gas supplies and flow control

Refer to Fig. 17. Hydrogen is employed to elute the compounds evolved in the soil ovens from the gas chromatograph and ^{13}C labeled carbon dioxide ($^{13}\text{CO}_2$) can be employed to purge the ovens during the oven heating period. Hydrogen is stored in a 7.5-cm-diam spherical aluminum tank.⁷⁹ The tank holds 240 cm³ at a pressure of 52 bars, which is sufficient for eight organic analyses at a hydrogen flowrate of 2–4 cm³/min with a depletion of less than one half of the hydrogen. The tank is constructed in halves of an aluminum alloy resistant to hydrogen embrittlement (alloy 2219). The halves are welded together. A gold disk seals the tank to a welded tube manifold assembly⁸⁰ at its opening. Attached to the manifold are a pressure transducer, a fill tube, and a containment valve.⁸¹ Valve detail is also shown in Fig. 17. The valve is used to contain the hydrogen while the instrument is being built. It is opened during transit of the spacecraft to Mars by releasing a spring-loaded plunger which then punctures the diaphragm. Prior to launch, the tank and valve assembly were cleaned by extensive ultrasonic rinses with various cleaning solvents followed by vacuum bake at 125°C and 10^{-7} Torr.⁸² During the vacuum bake, the vapors emanating from the assembly were monitored with a mass spectrometer. When the detected amounts of these gases fell below a predetermined level, the

tank was ready for filling. Filling consisted of analyzing a hydrogen stream being passed through a palladium alloy purifier, and using this stream to fill the tank when the impurities in the hydrogen were judged to be below threshold values. The tank was over-filled slightly, and the gas in the tank was analyzed by bleeding it through a palladium alloy separator into a mass spectrometer. Air and water levels were less than 1 ppm, and total organic compounds were less than 20 parts per billion (10^{-9}) in the hydrogen used. Tank pressure was then bled to 52 bars, and the fill tube was pinched off and leak tested.

The $^{13}\text{CO}_2$ cartridge⁸³ is a cylinder 0.6 cm i.d. by 4 cm long which holds 1.0 cm³ of $^{13}\text{CO}_2$ at a pressure of 52 bars. It is attached to valve V1 by a length of stainless steel tubing. The valve and cartridge are cleaned by vacuum bake, and the cartridge is filled. Valve V1 is then closed and the combined diffusion and leak rates of $^{13}\text{CO}_2$ through the valve are measured. The leak rate is less than 1×10^{-8} std cm³/s.⁸⁴

Flow control is maintained by dropping the high pressure in the gas supplies across a fixed, temperature-controlled restrictor.⁸⁵ The restrictors are a variation of the one previously described elsewhere.⁸⁶

G. Soil loader and pyrolyzer

The function of this subassembly is to accept pulverized soil samples from the soil processor, load these samples into the ovens, seal the ovens into the gas flow system, and heat the ovens to preselected temperatures of 50°, 200°, 350°, or 500°C during a soil analysis. Figure 18 shows an outline drawing of the mechanism.⁸⁷ Soil is loaded into an oven and prepared for analysis as follows: The oven is preheated to 500°C for 30 s to verify its function and to rid it of any materials which may have condensed on its inner surfaces. After cooling, the oven carriage⁸⁸ is rotated to position the oven under the soil funnel.⁸⁹ A soil sample is delivered to

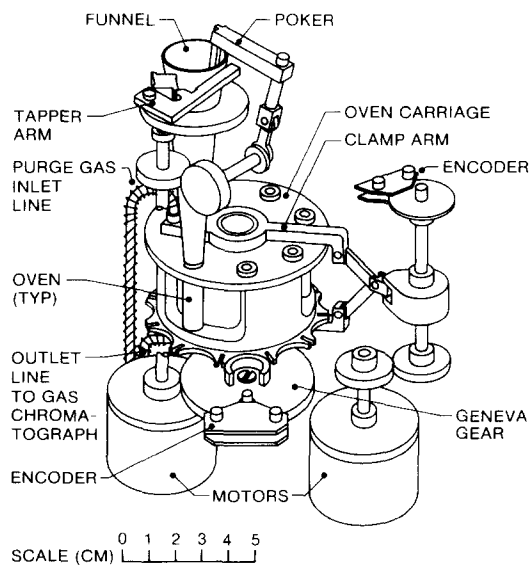


FIG. 18. Soil loader and pyrolyzer assembly.

the funnel by gravity from the soil processor. It is packed into the oven by means of a rod which slides up and down the inside wall of the funnel. At the same time the rod packs the soil, the funnel rotates, and a spring-loaded arm taps the outside of the funnel. This combined action was demonstrated to load a wide variety of soil samples, under simulated Martian gravity, at a funnel axis tilt up to 35° from vertical, in a time period less than 45 s.⁹⁰ After the oven is full (oven volume is $67 \mu\text{l}$), the carriage is rotated to position it between dual, circular knife edges. The knife edges close and penetrate the gold seals at each end of the oven, thus establishing a gas flow path between the soil and the gas chromatograph. The sample is then ready for heating.⁹¹ Heated tubes⁹² conduct the sample vapors to the gas chromatograph. The configuration of the mechanism is such that when the oven is positioned between the knife edges of the seal clamp, the soil funnel is located over a dump cavity in the carriage. Prior to positioning the carriage for loading of the next sample, the excess sample in the soil funnel is dumped into this cavity.

The carriage assembly is driven by a Geneva mechanism, which positions the ovens precisely for load and seal. The clamp assembly is a four-bar linkage, two of the pivots being located at the center shaft of the oven carriage.

As can be seen from Fig. 18, all mechanical functions are driven by two permanent magnet, incremental stepping motors⁹³: one drives the loader and carriage, and the other drives the clamp. Two clutches control the action of the loader and carriage drive mechanism; no clutch is used with the seal clamp motor, which is driven against fixed stops until it stalls. If the carriage is to be driven in the forward direction, the loader mechanism is disengaged by the action of a one-way

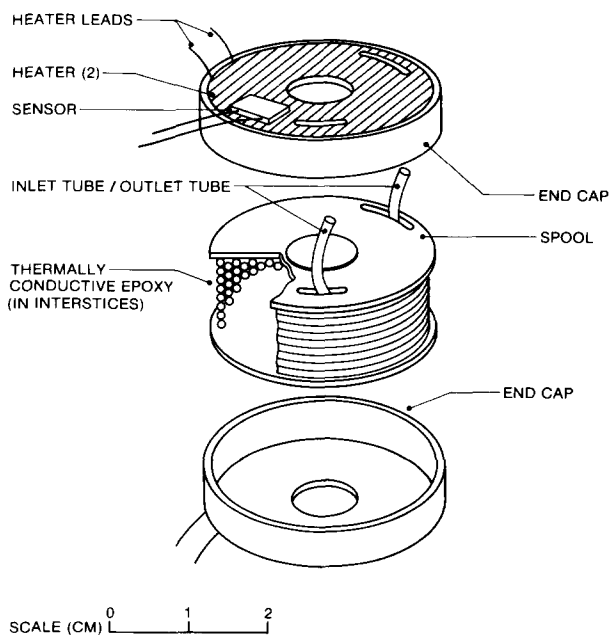


FIG. 19. Column packaging detail.

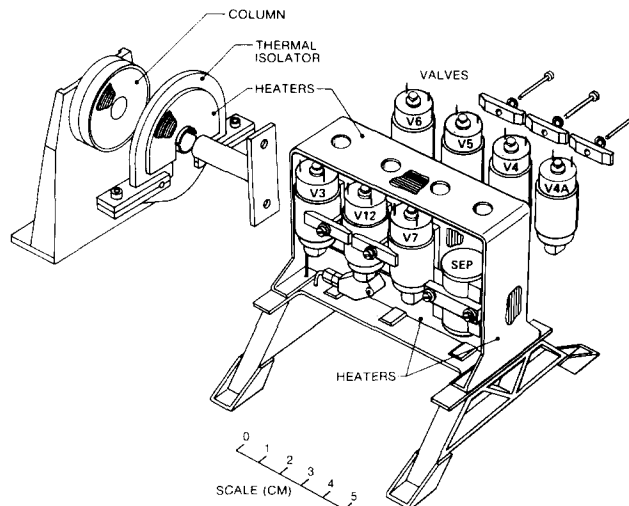


FIG. 20. Gas chromatograph, effluent divider, and separator locations.

clutch, and an electromagnetic clutch is engaged. If only the loader is to be operated, the motor is run in the reverse direction thus engaging the one-way clutch. If the carriage rotation is to be reversed, the electromagnetic clutch is engaged, and the motor is run in the reverse direction (thus causing the loader to run also). Carriage and clamp positions are verified by signals from light emitting diode-phototransistor pairs on the carriage and clamp.⁹⁴ These signals are fed into the GCMS computer and are used for verification of the proper function of the mechanism. If a carriage or clamp position test is failed, the computer aborts the sequence, returns to the standby mode, and waits for a command from the lander, *ergo* Earth.

During assembly, the loader and pyrolyzer assembly is cleaned using procedures modified from those developed for cleaning of tools used on Moon rocks.⁹⁵ In addition, all piece parts are vacuum baked at their highest storage temperature (as specified by the manufacturer). After assembly, the mechanism is vacuum baked again at 133°C . During this bake, the ovens and connecting lines are heated and their outgassing products are measured with a mass spectrometer. The subassembly is mated to the soil processor and the combined assembly is hermetically sealed. A positive pressure of approximately 1.3 bars of nitrogen is maintained in the combined assembly until launch. The assembly is vented during transit to Mars by opening valve V13 (Refer to Fig. 9). This valve is closed prior to entry to prevent propellant gases from entering the system. The lid on the soil processor is opened two Martian days after landing.

H. Chromatographic column

The performance characteristics and packing details of the column⁹⁶ have been given.⁹⁷ Figure 19 shows the way in which the column is wound and heated, and Fig. 20 shows how it is connected into the system. The column is thermally isolated from hotter areas of the

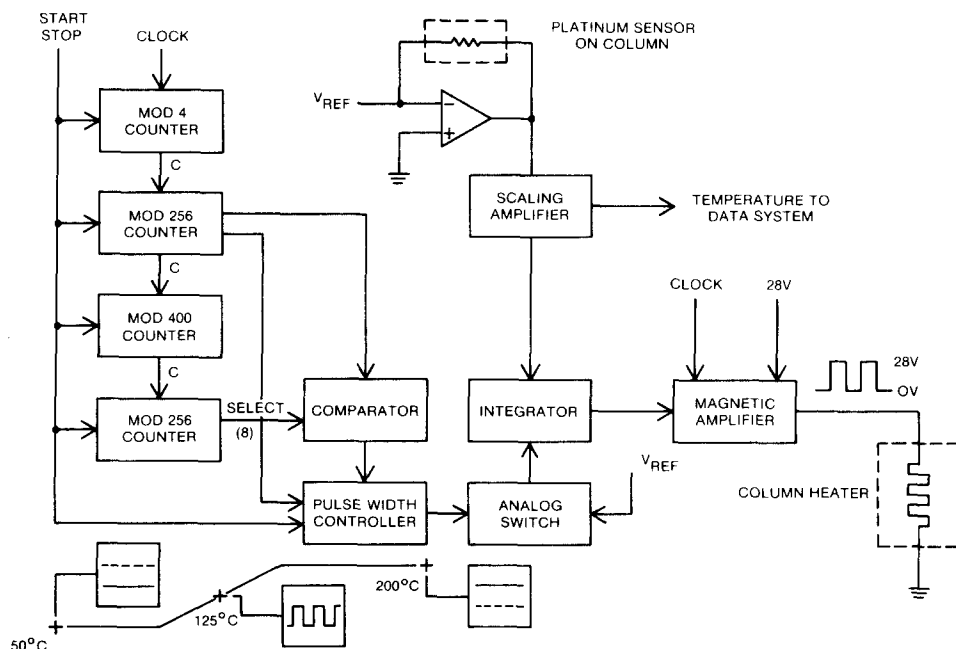


FIG. 21. Column temperature controller block diagram.

instrument using an aluminum disk⁹⁸ which is a heat sink for the transfer lines. Heaters on this disk are temperature programmed with the column to prevent cold spots from developing on these lines during column heating.

I. Column temperature control

After sample injection, the column is held isothermally at 50°C for 10 min, ramped linearly to 200°C at 8.3°C/min and held at 200°C for a preselected time period of 18, 36, or 54 min. As shown in Fig. 21, a proportional type controller⁹⁹ is used to control column temperature. The linear ramp control function is obtained from a 4-kHz repetitive pulse of variable duty cycle. The duty cycle is varied linearly from 0% to 100% between 50°C and 200°C. This in turn drives a switched reference voltage which is integrated, providing an analog reference of the desired temperature profile. Feedback from a platinum wire temperature sensor mounted on the column spool assembly is compared with

the control function to provide the correction signal to the heaters. The control point is stepped approximately every 4.2 s during the ramp. Temperature control is better than $\pm 0.1^\circ$ as measured at the sensor.

J. Valves, fittings, manifolds, and tubulation

Special valves were developed for applications within the GCMS. The valves (except valve V0) are all electrically actuated with a 12-ms current pulse and magnetically latched. Figure 22 shows a cross section of one of the three-port valves used in the effluent divider.¹⁰⁰ Two-port valves¹⁰¹ possess the ports adjacent to the valve poppet only. The gas flow system is configured such that sample exposure to internal valve surfaces is minimized. In addition, certain valves were fitted with a stainless steel liner which prevents samples from contacting surfaces of nickel. Table V summarizes valve configurations.

Tube fittings¹⁰² are used to assemble the various components into a total system. A detail of one of these fittings is shown in Fig. 22. The seal relies on a polyimide gasket¹⁰³ which is compressed by torquing the fitting.

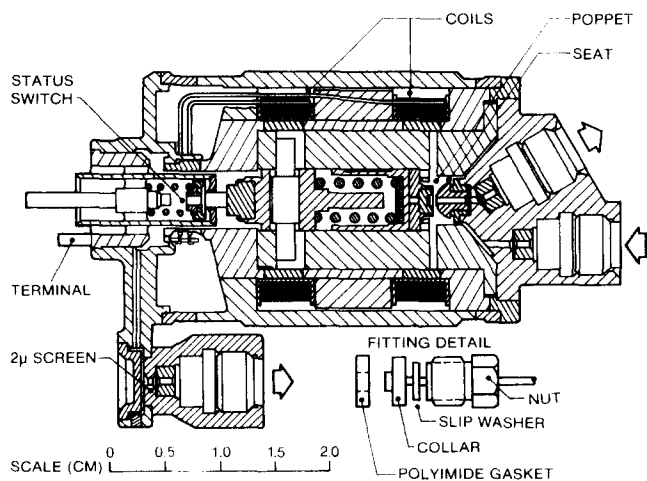


FIG. 22. Valve and fitting detail.

TABLE V. Valve configurations and end of life leak rates.

Valve	Special feature	Config-uration	Leak rate (std cm ³ /s He at 1 atm ΔP)	
			Lander ambient	225°C operating
V1, V2	High pressure	2-port	1.5×10^{-8}	N/A
V3, V7	High temperature	2-port	4.0×10^{-8}	2.0×10^{-6}
V4, V5, V6	High temperature	3-port	N/A	3.0×10^{-6}
V4A, V12	High temperature	2-port	4.0×10^{-8}	2.0×10^{-6}
V9	High conductance	2-port	4.0×10^{-8}	N/A
V10	High conductance	2-port	5.0×10^{-5}	N/A
V11	High conductance	2-port	4.0×10^{-6}	N/A
V13	—	2-port	5.0×10^{-6}	N/A

The fitting was designed to reduce dead volume to less than 5 μl .

Tube manifolds¹⁰⁴ are employed in locations in which volume considerations are critical and where assembly and disassembly are not required. The manifolds consist of 2–5 tubes brazed into a small block of metal (the manifold body). The bodies are bored through for gas passages, then counterbored to accept the tubes, and then counterbored again to accept the braze alloy. This technique provides a reliable braze joint which shows 100% coverage of the braze counterbore when the joint is x-rayed.

Tubulation is either type 316L Chromat stainless steel¹⁰⁵ or gold–platinum (94:6) alloy.¹⁰⁶

K. Effluent divider

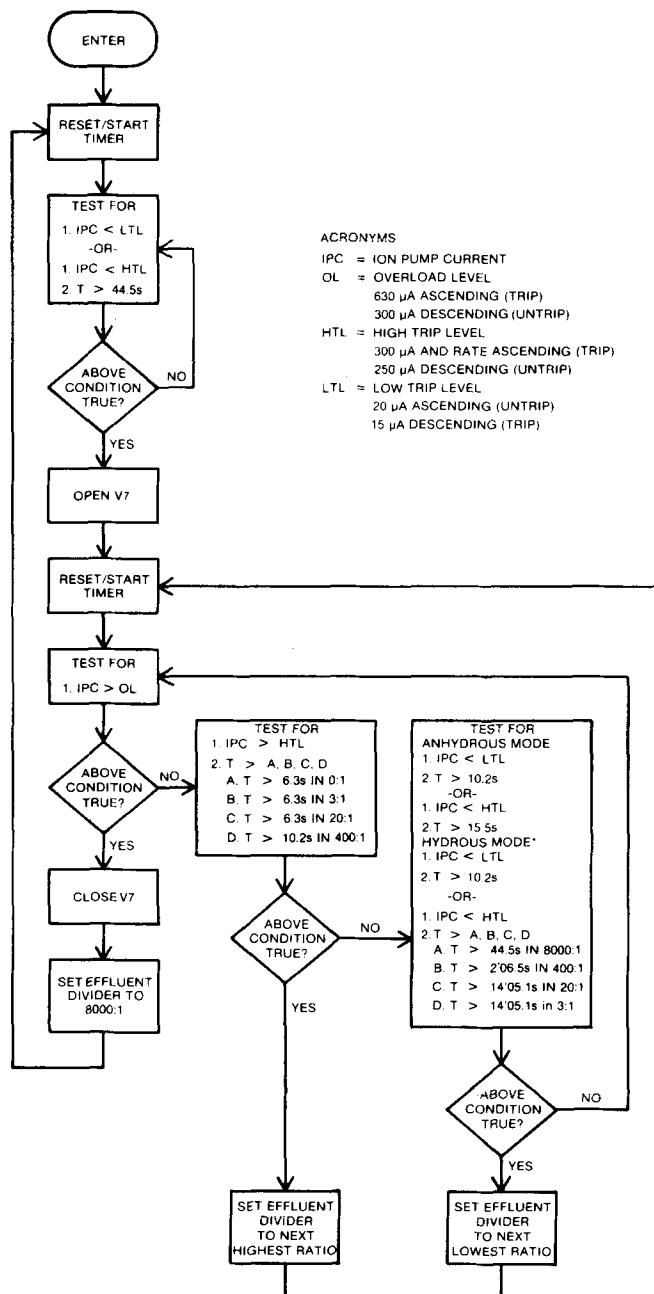
This network of tubes, valves, restrictors, and manifolds controls sample flow into the mass spectrometer. It is temperature controlled¹⁰⁷ at 218°C to prevent sample condensation. Valve, tube, and manifold volumes are minimized to reduce response time. Valves V7, V5, V6, and V4 are opened sequentially to permit more sample to flow into the MS, and finally valve V4A is closed to direct all of the sample to the MS.

L. Effluent divider control

The mass spectrometer ion pump provides the control signal to the effluent divider control computer. The signals sent by the ion pump are in the form of discrete discriminator signals. These signals are as follows: an “overload” signal¹⁰⁸ is generated if the ion pump current exceeds 630 μA , and is removed when the signal falls below 300 μA . A “high-level” signal is generated if the level of the ion pump current plus the rate of rise of ion pump current¹⁰⁹ indicate the approach of an overload, according to the following:

$$D = \ln I + k[d(\ln I)/dt],$$

where D is the discriminator signal, I is the ion pump current, and k is the rate control constant. The “high-level” signal is removed when the ion pump current falls below 250 μA . A “low-level” signal is generated when the ion pump current falls below 15 μA , and is removed when the current rises above 20 μA . The three signals correlate roughly to ion source pressures of 5×10^{-5} , 2×10^{-5} , and 1×10^{-6} Torr, respectively. A control algorithm for the effluent divider is shown in Fig. 23. Note that the effluent divider is controlled not only by the discriminator levels, but also by the dwell time in each effluent divider state. The times were empirically determined by analyzing a large number of samples with the system. Notice also that two modes are employed, designated “hydrous” and “anhydrous.” The hydrous mode was necessitated by large water overloads, which are slow to elute from the chromatographic system (the pressure reduction may be as great as 10^5).



*NOTE: WHEN THE HYDROUS MODE IS SELECTED, THE CHANGE FROM ANHYDROUS TO HYDROUS OCCURS 45 SECONDS AFTER THE OVEN HEATING PERIOD ENDS.

FIG. 23. Effluent divider control algorithm.

The effluent divider control computer is shown in block diagram in Fig. 24. A 64-word (8-bit word) PROM controls the test sequence which is decoded by the control logic. Output signals are sent to the valve drivers. The computer requires that the valves be set to a preselected state when it is commanded on (all valves closed except valve V4A). Feedback from the valve status indicators is not employed, i.e., the computer does not command on the basis of valve position—it commands based on the algorithm alone.¹¹⁰

M. Separator

Construction and operating details of the palladium alloy separator have been presented elsewhere in

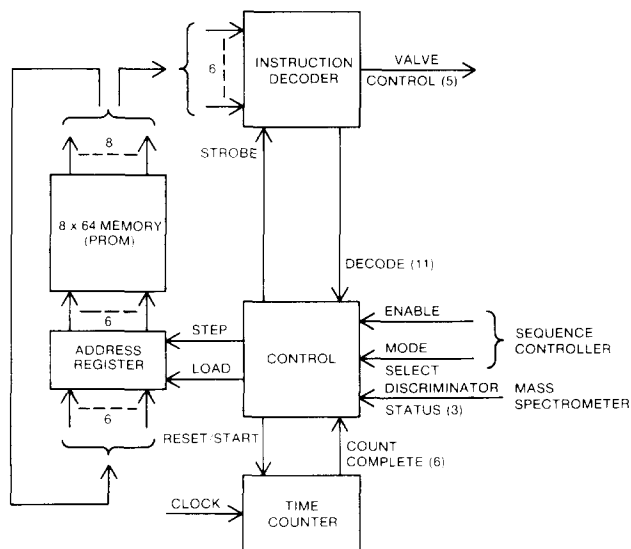


FIG. 24. Effluent divider control computer block diagram.

detail.¹¹¹ A recent improvement in separator reliability has been achieved by more stringent quality control of the palladium alloy tubing.¹¹²

IV. GROUND DATA SYSTEM

Data from each lander are received through the three space network stations, and are recorded and processed as shown in the diagram in Fig. 25. Analog recording of the signal takes place at each space network station. Simultaneously, the signal is transmitted to the Mission Control Computing Facility at the Jet Propulsion Laboratory (JPL) in Pasadena, CA. Upon receipt at JPL, the signal is decoded and displayed on cathode ray tube (CRT) monitors and on-line printers, and is recorded for further processing. When GCMS data are present, they are displayed on the CRT monitors, and on-line and character printers in a GCMS-specific octal format. Both the engineering and mass spectrometer output data can be displayed; however, the MS output data are so voluminous (4 kilobits/s) that they cannot be printed in real time; hence the engineering data alone are viewed to verify proper operation of the instrument, and to provide information on which to base future commands.

After transmission from the spacecraft is complete, a file of data from all lander science instruments is produced. This file is then split into smaller files, one for each instrument. The GCMS data receive final processing from this file through the Atmospheric and Organic Analysis Program (ATMORG),^{113,114} which was developed from algorithms and techniques originating at the Massachusetts Institute of Technology (MIT).¹¹⁵⁻¹¹⁷ The outputs from ATMORG are in the form of printouts, mass spectral plots, and microfilm. Engineering data are processed using the calibration curves determined during instrument test, and the temperatures, pressure, etc. are displayed in appropriate units ($^{\circ}\text{C}$, bars, etc.). Mass spectral data are

processed by use of an algorithm which finds the maximum value of the resolved ion current within a given m/e window, and using this mass-intensity value for subsequent data reduction. In printout of the atmospheric data, the maximum current at each m/e for each scan is listed and the currents are averaged over each set of background and gas sample scans. A corrected scan is produced in which the averaged background scans are subtracted from the averaged gas sample scans. Partial pressures and percent abundances are computed using calibration data taken from each instrument during construction, and from similar instruments on earth. Soil analysis data are reduced by normalizing each mass spectral peak to the maximum peak in the spectrum, in the presence or absence of peaks below m/e 48. These data are displayed on microfilm as linearized, normalized bar graphs of the mass spectrum (with and without deletion of peaks below m/e 48). In addition, "Mass Chromatograms"¹¹⁶ are displayed on microfilm for each m/e value in the scan range of the instrument, and a "Sum of Intensities" or "Total Ionization" plot is produced by summing the intensity of each m/e value in a scan and plotting these sums as a function of analysis time.

Magnetic tapes of GCMS data are shipped to MIT for further data processing. A two-way computer link between JPL and MIT provides for the interactive analysis of data on a CRT terminal at JPL driven by the MIT computer. This link permits library searches, subtraction of "cruise" backgrounds (see Sec. V B) and "reconstruction" of spectra from the mass chromatograms.¹¹⁷

V. INSPECTION AND TESTING

Starting at the individual component level, each part is inspected and tested for conformance to the specifica-

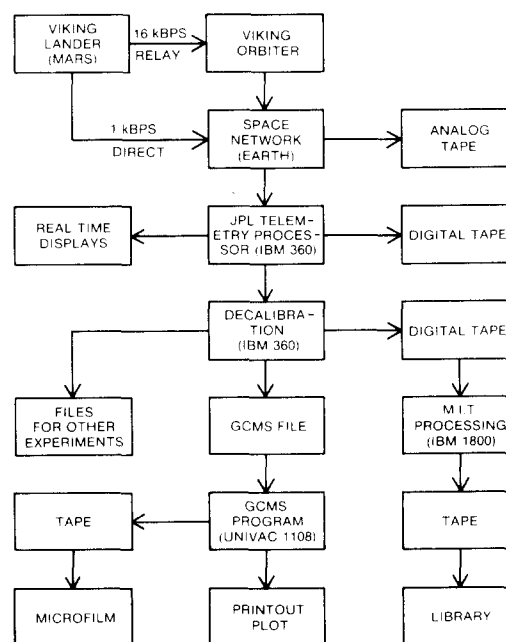


FIG. 25. Data processing block diagram.

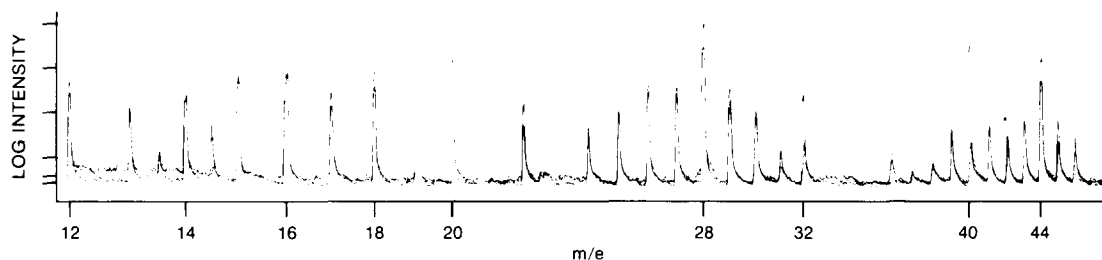


FIG. 26. First mass spectra returned from Mars.

tion for that part. As subassemblies are built, inspection and test occurs at each functional level. This process continues through the final assembly of the instrument. The procedures followed for a specific inspection and test are a subset of generalized procedures.^{118,119}

A. Pre-launch testing

After final test of the instruments at the manufacturer's, they were shipped to Kennedy Space Center and installed in the Viking Landers. Test of the Lander/GCMS combination was performed to verify compatibility. The Landers were then sterilized and the GCMS instruments retested. During the retest it was discovered that the GCMS on Lander 1 had developed a leak in the mass spectrometer vacuum envelope. After extensive tests to assure that the leak would not worsen, it was decided to launch the instrument with the leak.

B. Cruise testing

During the transit between Earth and Mars, the GCMS instruments on both landers were tested. A "blank" analysis was performed on one oven on each lander and the atmospheric backgrounds within the instrument were measured. These tests revealed that all elements of the system were operating properly, with the exception of the loss of the capability to heat one soil oven on each lander and the loss of one of the encoder signals from the oven carriage of the instrument on Lander 2. The loss of the soil ovens was of little ultimate consequence, principally due to the homogeneity of the Martian soil,¹⁴ and the loss of the encoder signal was offset by the use of backup sequences which ignored the faulty encoder signal and successfully positioned the oven carriage during the landed mission.

C. Landed performance

A summary of the detailed tests performed by the GCMS instruments on both landers is now available.¹²⁰ A total of 14 organic analyses were performed on the 4 soil samples and 57 analyses were made of the Martian atmosphere during the primary mission. Figure 26 shows the first mass spectra returned to Earth from the surface of another planet (three background scans and four sample scans are overplotted). This atmospheric analysis was performed with removal of CO, CO₂, and H₂O. The backgrounds present in the mass spectrometer

were caused by ingestion of terrestrial vapors through the vacuum leak which occurred in pre-launch testing.

ACKNOWLEDGMENTS

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^{a)} To whom requests for information should be addressed.

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⁵ Rick Gore, *National Geographic* **151**, 1 (1977).

⁶ Documentation of parts, assemblies, schematics, and procedures given in these references can be obtained either on loan or permanent copy from the following sources, as referenced:

(a) Viking Project Office, Langley Research Center, Hampton, VA 23665; (b) Viking Office, Martin Marietta Aerospace, P.O. Box 179, Denver, CO 80201; (c) D. W. Howarth, Litton Systems, 5500 Canoga Avenue, Woodland Hills, CA 91364; (d) Beckman Instruments Inc., Advanced Technology Operations, 1630 S. State College Blvd., Anaheim, CA 92806; (e) Perkin-Elmer Aerospace, 2771 N. Garey Avenue, Pomona, CA 91767.

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- ⁴³ Heater Assy P/N 345955, Ref. 6(e).
- ⁴⁴ Leak Assy P/N 345610, Ref. 6(e).
- ⁴⁵ Manifold Assy P/N 347388, Ref. 6(e).
- ⁴⁶ Electrostatic Analyzer P/N 1125600, Ref. 6(e).
- ⁴⁷ Ion Beam Alignment Assy P/N 345543, Ref. 6(e).
- ⁴⁸ Pinch Tube Assy P/N 345929, Ref. 6(e).
- ⁴⁹ Ion Pump Assy P/N 1125510, Ref. 6(e).
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- ⁵⁵ Initial development of the mass spectrometer electronics was carried out by J. O. Maloy, J. H. Marshall III, and R. Loveland.
- ⁵⁶ DC/AC Converter P/N 346186, 346214, Ref. 6(e).
- ⁵⁷ EMT Supplies P/N 346225, 346165, Ref. 6(e).
- ⁵⁸ EMT Gain Select P/N 346161, Ref. 6(e).
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