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The Biology Instrument for the Viking Mars Mission

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Two Viking spacecraft have successfully soft landed on the surface of Mars. Each carries, along with other scientific instruments, one biology laboratory with three different experiments designed to search for evidence of living microorganisms in material sampled from the Martian surface. This 15.5-kg biology instrument which occupies a volume of almost 28.3 dm^3 is the first to carry out an *in situ* search for extraterrestrial life on a planet. The three experiments are called the pyrolytic release, labeled release, and gas exchange. The pyrolytic release experiment has the capability to measure the fixation of carbon dioxide or carbon monoxide into organic matter. The labeled release experiment detects metabolic processes by monitoring the production of volatile carbon compounds from a radioactively labeled nutrient mixture. The gas exchange experiment monitors the gas changes in the head space above a soil sample which is either incubated in a humid environment or supplied with a rich organic nutrient solution. Each experiment can analyze a soil sample as it is received from the surface or, as a control, analyze a soil which has been heated to above 160°C. Each instrument has the capability to receive four different soils dug from the Martian surface and perform a number of analysis cycles depending on the particular experiment. This paper describes in detail the design and operation of the three experiments and the supporting subsystems.

I. INTRODUCTION

The United States has successfully sent two identical unmanned spacecraft, each consisting of a soft lander and an orbiter, to Mars in the 1975 launch opportunity. The project called Viking[1-4] has placed both landers safely on the Martian surface. Each lander carries, along with several other scientific instruments, an instrument to search for living organisms in Martian surface material. This Viking biology instrument is the first device to be put on the surface of another planet to conduct life detection experiments.

The instrument contains three separate biological experiments which analyze the Martian surface material for microorganisms by three different methods. The pyrolytic release experiment is designed to measure either photosynthetic or chemosynthetic fixation of CO_2 or CO into organic compounds.[5,6] The labeled release experiment tests for the presence of metabolic activity during incubation of a surface sample that has been moistened with a dilute aqueous solution of carbon-14 labeled simple organic compounds.[7-9] The gas exchange experiment detects changes in the concentration of metabolic gases above a soil sample which can either be incubated in the presence of only water vapor and Mars atmosphere or wet with a rich, nonradioactive, aqueous nutrient solution.[10,11]

The concepts for planetary life detection experiments have been seriously pursued and laboratory models of some of these concepts have been tested since the late 1950s and early 1960s.[12,13] Throughout the 1960s several different experiments were suggested for detection of extraterrestrial life based on various physical, chemical, and biological approaches.[14,15] With the approval in 1969 of Viking as a landed Mars mission, the current three experiments along with a fourth, the light scattering experiment, were selected in November 1969 by NASA after a review of proposals solicited from the scientific community at large. In addition to the scientists who developed these experiments, three additional scientists, not associated with one particular experiment, were also selected to form a science team. Table I presents the composition of the resulting Viking Biology Team. The fourth experiment, light scattering, was deleted from the instrument package midway during the development period after detailed engineering and planning studies indicated there was little chance that a four-experiment instrument could successfully be manufactured and

TABLE I. NASA selected team for Viking active biology investigation.

H. Klein (Ames), Team Leader	
W. Vishniac[a] (U. of Rochester), Asst. Team Leader	Light Scattering
H. Horowitz (JPL, Cal Tech)	Pyrolytic Release
G. Levin (Biospherics, Inc.)	Labeled Release
V. Oyama (Ames)	Gas Exchange
A. Rich (MIT)	
J. Lederberg (Stanford)	

[a] Prof. Vishniac died in an accident in 1973 while conducting Viking-related experiments in Antarctica.

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tested within the temporal and fiscal constraints imposed by the mission.

Multiple experiments were chosen on the basis that no single life detection experiment would be adequate for the first landed mission to Mars. As a result, the experiments are based on different assumptions about the characteristics and function of any Martian biology. In general, the experiments range from incubation conditions which closely simulate those on Mars (the pyrolytic release experiment which adds no water and no nutrient compounds) through an intermediate environment (the labeled release experiment which moistens the soil with a nutrient of simple, dilute organic compounds in water), to rather earthlike conditions (the gas-exchange experiment which in its wet mode partially submerges the Martian soil in a rich and complex solution of salts and organic compounds). These experiments present a coordinated experimental system of environments for stimulating and measuring the manifestation of possible Martian soil organisms.

Development of the Viking biology instrument was begun in 1970 by TRW Systems, Redondo Beach, CA, under contract to Martin Marietta Corp. as the lander prime contractor, and continued for 5 years of design, fabrication, and test until delivery of the flight units in the spring of 1975. Three instruments (two flight instruments, and one spare) capable of conducting the landed mission and four test instruments were assembled. The two flight instruments are currently on the Martian surface and all three experiments in each instrument have operated successfully. Preliminary results from the biology experiment have been published[16–19] and complete descriptions of the scientific data obtained on Mars will be the subject of subsequent papers.

II. INSTRUMENT SYSTEM DESCRIPTION

A single instrument of the complexity required to conduct the three active biology experiments has never before been assembled for space flight. The instrument's overall physical characteristics are given in Table II. The complexity of the instrument arises because of the large number of different functions which must be performed to conduct the biological analysis of the Martian surface material. Small amounts of soil are transported, tiny amounts of gases and liquids are metered, gas flowrates are controlled, 750 °C temperatures are reached, and soil temperatures are held below those of the surrounding environment by thermoelectric cooling systems. Extremely leaktight and resealable test cells are used so that the minute quantities of gases in the incubation cells will not be lost. Two of the experiments utilize nuclear detector systems which detect picomole quantities of carbon-14 in the presence of a large radiation background from the radioisotope thermoelectric generators that power the Viking lander. A miniaturized gas chromatograph measures parts per million (ppm) concentrations of metabolic gases such as methane. Illumination simulating the spectrum, minus the ultraviolet, of the sun on Mars is provided by a miniaturized high-pressure xenon arc lamp. To conduct these operations the instrument contains 39 solenoid valves, 43 heaters, 4 thermoelectric coolers, 4 heat pipes and 3 types of thermal controllers, 4000 mechanical parts, and 1800 electronic parts. Because of the small passages and orifices (0.0076 cm) required by the small allowable physical size of the package, special steps were taken to prevent particle contamination or guard against its interference. The instrument was assembled under stringent "clean room" conditions and contains 11-μm pore-size filters to prevent particles from plugging critical flow restrictors.

TABLE II. Biology instrument physical characteristics.

Weight	15.5 kg
Volume	0.027 m^3
Power consumption	
Average	12 W
Maximum	180 W
Data generation	
Average	10 000 bits/sol
Maximum	50 000 bits/sol
Capacity for surface samples	4 surface acquisitions

The biology instrument resides along with other science instruments and electronic assemblies in the interior of the lander in a thermally controlled environment (−5° to +27 °C). All electric power is obtained from two radioisotope thermoelectric generators which have the capability of providing average power of about 60 W.

Located directly above and mounted to the biology instrument is the soil sample processor and distribution assembly (SSPDA) (tall, vertical column in right photo of Fig. 1). This assembly protrudes upwards through the equipment mounting plate so that it can receive soil from the surface sample collector head. The collector head, mounted on the end of a 3.05-m furlable boom of the Viking lander (left photo of Fig. 1), has the capability of collecting material from a preselected site on the Martian surface. After collecting the sample, the boom retracts and deposits the soil sample in the top of the SSPDA. The soil is filtered through 1.5-mm screen at the top of the SSPDA to reduce the soil particle sizes to levels compatible with the biology instrument. A measured amount of soil, nominally 6 cm^3, is then metered and delivered to the biology instrument.

The biology instrument's interfaces with the lander (as shown in Fig. 2) include the power control and distribution assembly which provides bus voltage to the instrument, the guidance and control and sequencing computer (GCSC) which provides clock signals and commands to the instrument, and the data acquisition and processor assembly which collects the data from the biology instrument for later transmission either to the orbiter or direct to earth. In addition to these

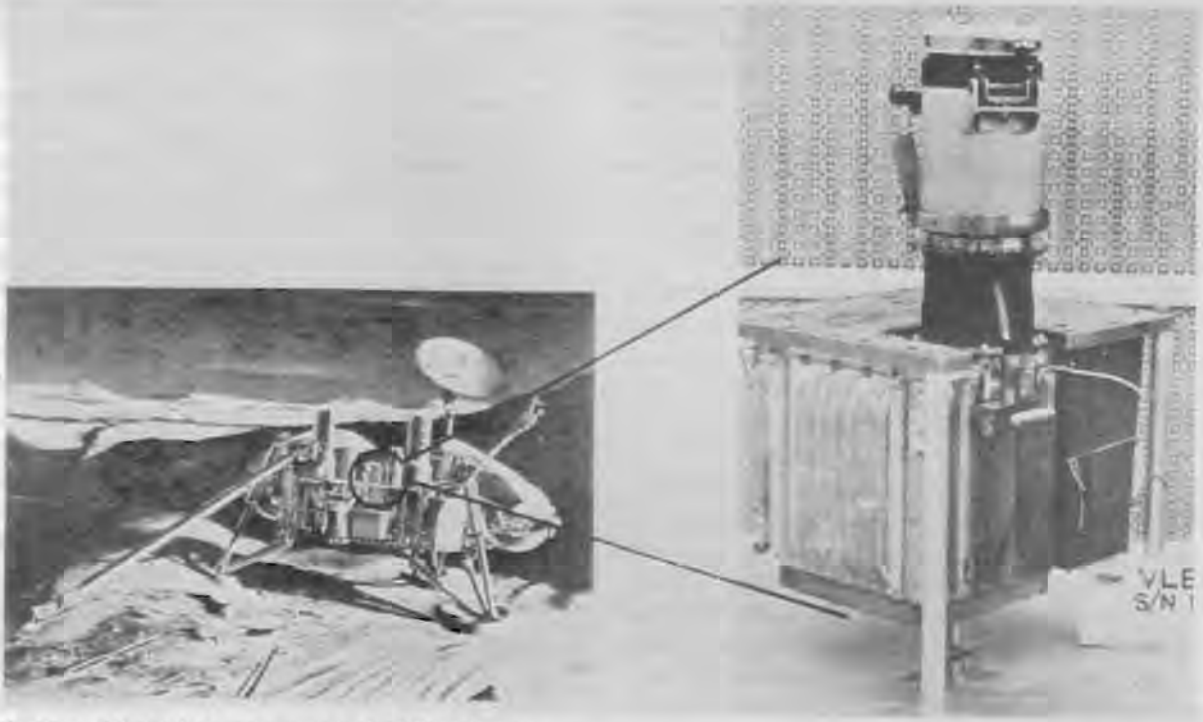

FIG. 1. Position of the biology instrument in the Viking Lander.

electrical interfaces, the instrument is exposed to the Martian environment through the SSPDA. Waste gases and vapors are brought out of the lander through three gas and one vapor vent lines.

The three biology experiments have been integrated in one instrument sharing common support equipment. The biology instrument is packaged in two separate assemblies (Fig. 3), the mechanical subsystem (MSS) and the electrical subsystem (ESS), each of which is mounted directly to the lander equipment mounting plate. The MSS and ESS are connected by an electrical cable.

The ESS receives commands from the GCSC, uses those commands to control the individual experiments, and receives and processes the data for transmission to the data acquisition and processing unit. The control functions performed by the ESS involve timing and operating of all solenoid valves, nine proportionally controlled heaters, five electronic thermostats, and

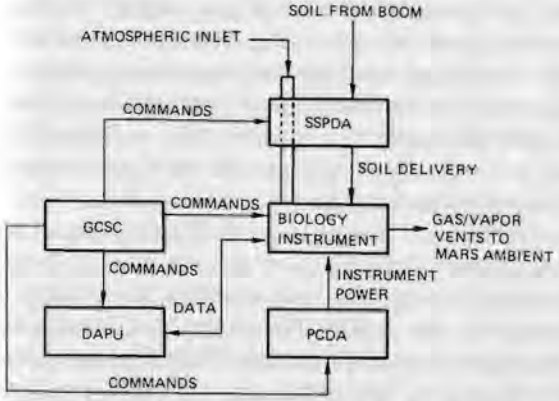

FIG. 2. Block diagram of the Viking Lander as related to the biology instrument. The biology instrument receives soil from and Martian atmosphere through the soil sample processing and distribution assembly (SSPDA). The instrument is under control of the guidance, command and sequencing computer (GCSC) and receives its power through the power conditioning and distribution assembly (PCDA). The biology data memory is transferred to the data acquisition and processing unit (DAPU) before storage of the Lander tape recorder.

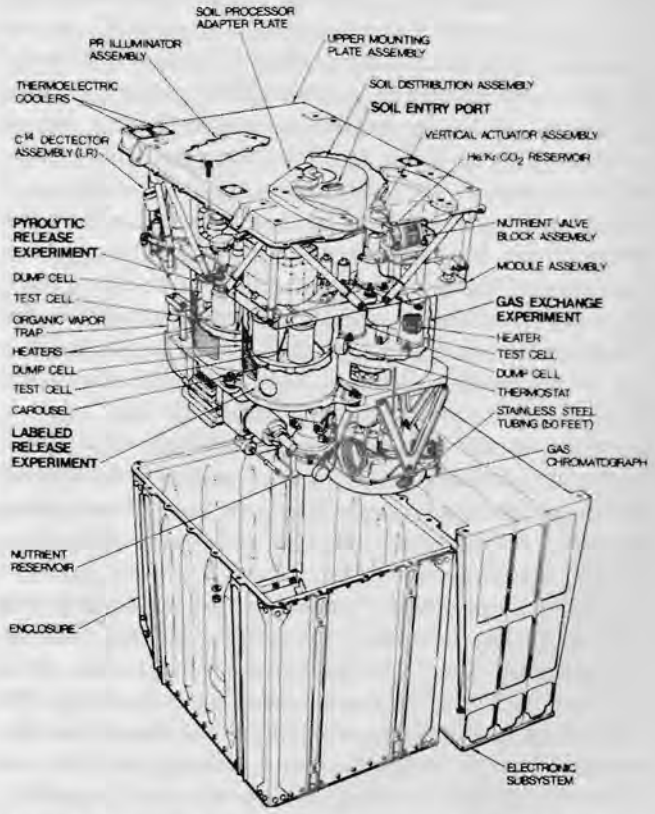

FIG. 3. Sectioned view of the instrument mechanical package showing the three experiments with their functional detail.

power switching for eight mechanical thermostats in the MSS. The ESS receives the individual experiment sensor outputs and temperature outputs and processes those outputs for storage. If the data are analog, as is the case of temperature measurements, they are amplified, commutated, and processed with a dual slope analog-to-digital converter, identified, and then stored in a 120-word solid state memory. Digital data such as the ^{14}C counts and commands are identified and stored in the memory. The sequence control of the MSS is provided with three read only memory (ROM) sequencers which perform timing and control functions as directed by the commands from the GCSC. The individual sequence functions of the instrument are stored within the ROM sequencer with the GCSC commands directing blocks of these activities to occur at appropriate times during the experiment cycle.

The MSS (Fig. 3) is designed as a modular concept. The three experiment modules, gas exchange (GEx), labeled release (LR), and pyrolytic release (PR) are integrated with the common services module (CSM), the nuclear detection system, the soil distribution assembly (SDA), and the PR illumination assembly to form the MSS. Each of the modules is assembled and tested as a separate entity prior to integration into the MSS.

The GEx is designed to incubate a soil sample in the presence of a rich nutrient. This experiment contains a single test cell and one soil dump cell mounted on a carousel which can be dropped and rotated so as to position either the test cell or the dump cell at the head end or the load port. The soil is obtained from the SDA and rotated to the incubation head end. At the incubation head end the chamber is sealed and an incubation atmosphere is created for the sample. This involves providing a gas mixture within the cell, which contains CO_2 to simulate the Martian atmosphere, helium to provide the pressure required for obtaining a gas sample, and krypton to be used as an internal standard gas for the gas chromatograph. In all three experiments, temperature control is provided by means of heaters and thermoelectric coolers to maintain the temperature between 5° and 27 °C. Nutrient is injected into the incubation chamber, first in a mode to provide only a humid environment in the cell and later to actually wet the soil. At periodic intervals during the incubation gas in the headspace is sampled and analyzed using a gas chromatograph. The data from each of these analyses are stored in the ESS and later transmitted through the lander to earth.

The LR experiment is designed to incubate a soil sample in the presence of a radioactively labeled (^{14}C) nutrient. This experiment has four test cells, again mounted on a carousel permitting the use of any one of the four for a given experiment. No dump cells are provided on LR. Rather, waste soil is deposited in the used test cells after each experiment cycle is complete. To perform an experiment the soil is obtained from the SDA and rotated to the incubation head end. As in GEx, the chamber is sealed and the incubation atmosphere established. A small quantity of aqueous nutrient is then injected onto the soil. This liquid contains low concentrations of radioactively labeled (^{14}C) carbon nutrients which might serve as substrates for any organisms which might exist in the soil. As growth occurs, radioactively labeled gases are generated in the headspace above the soil. This headspace is continuously monitored by a separately packaged nuclear detection system for the duration of incubation, thereby monitoring any gases generated. The data are stored and later transmitted to earth by the lander.

The PR experiment is designed to incubate a Martian soil sample in the presence of a radioactively labeled CO/CO_2 atmosphere. This experiment contains three test cells and three soil dump cells mounted on a carousel. In addition, simulated Martian sunlight is provided by a xenon lamp. A small sample of soil is received from the SDA and rotated to the incubation head end. The chamber is sealed and a $^{14}CO/^{14}CO_2$ gas mixture is injected into the cell. An option exists to add a minute amount of water vapor to the chamber at this time. The lamp is turned on and the system allowed to incubate for 5 days. Organisms may assimilate carbon from the radioactive gas and therefore become radioactively labeled. After the incubation period, the incubation atmosphere is vented and the cell rotated to the pyrolysis head end. There the soil sample, which may now contain radioactive carbon organics, is pyrolyzed by raising its temperature to 625 °C, and the vaporized organics trapped in an organic vapor trap. These organics are then converted to CO_2 by an "elution" heating of the trap and counted by the separate nuclear detection system. The data are stored in the ESS and later transmitted to earth for analysis.

The common services module contains a common helium source for the three experiments. About 77 000 standard cm^3 of helium are available for instrument operation. The primary use of the helium is as a carrier gas for the gas chromatograph in the GEx experiment; hence, it is called the carrier gas supply (CGS). It is, however, used by other experiments to move cells, purge chambers, and for various other operations. A liquid vent system is also provided which is shared by LR and GEx which vaporizes the expelled liquids, traps any organics in a charcoal filter, and expels the remaining water vapor.

The MSS also contains a soil distribution assembly (SDA). The SDA receives 6 cm^3 of soil from the soil sampler processor and distribution assembly. At the start of the experiment cycle, soil distribution is made to the three experiments. The SDA operation involves metering and delivering 1.0 cm^3 of soil to the GEx, 0.5 cm^3 to the LR, and 0.25 cm^3 to the PR. The remainder of the soil is retained in the SDA to provide a sample of the same soil should a decision be made to make a control (sterilized) run. At the end of an experiment and after the control decisions have been made, any remaining soil is removed by depositing into the

individual experiment dump cells by driving the SDA in a soil delivery mode.

III. STERILIZATION REQUIREMENTS

An extraterrestrial life detection instrument has placed upon it several unusual requirements. One of the most unique is that the instrument must be capable of being sterilized by dry heat.

Because it is the goal of the biology instrument to detect indigenous life on Mars, there are two reasons for heat sterilization of the instrument and the lander to significantly lower the biological contamination contained thereon: (1) reduce the probability of the biology instrument detecting Earth organisms carried to Mars to less than one chance in a million, and (2) reduce the probability of the Viking mission contaminating Mars with Earth organisms to less than one in ten thousand. While the rationale for these requirements is obvious, the responsibility to assure that any detected life responses are from Martian and not Earth organisms is overwhelming.

These requirements were satisfied by a double dry heat sterilization, one of the instrument alone, and then one of the entire lander with the biology instrument installed. The sterilization prior to installation into the Viking lander is unique to the biology instrument (as compared to the other lander instruments), because the biology instrument provides an environment where viable microorganisms are encouraged to metabolize and reproduce. Under these circumstances Earth microorganisms could be indistinguishable from Martian organisms.

In the preinstallation sterilization, the instrument was heated to 120 °C for 54 h in a dry nitrogen atmosphere and cooled in the sterilization oven. In order to prevent recontamination during shipping and installation, the instrument was handled in the following manner to prevent airborne particles from entering or landing on it. The instrument was kept covered in post-sterilization testing by sterilized nylon covers, and personnel handling the hardware wore sterilized caps, gowns, and gloves. Gases admitted to the post-sterilization test chambers were filtered through 0.45-μm membrane filters. The instrument was shipped to Kennedy Space Center in a sterilized nylon bag.

During installation of the biology instrument in the Viking lander, handling precautions were taken to minimize any possible recontamination of the hardware. After installation on the lander, the entire lander was encapsulated in a "bioshield" which was not opened until after launch and the spacecraft had left the Earth's atmosphere. While in the bioshield, the lander and biology instrument were heated to 112 °C for 26 h in a dry nitrogen atmosphere at 1 bar. From the time of this sterilization onward, the biology instrument was protected by the bioshield and never again exposed to the airborne microflora of the earth's atmosphere.

The results from the two biology instruments on Mars are consistent with insufficient viable Earth organisms to contaminate the biology experiments. The gas exchange experiment which is most earthlike in its incubation conditions has shown no evidence of gas changes associated with microbial metabolism in as much as 200 days of incubation on Viking Lander 1.[16,17] This experiment provides an environment of 10 °–12 °C, a 2 : 1 water-to-soil ratio, a nutrient rich in amino acids, carbohydrates and salts, and pressure averaging about 200–600 mbars. Under these conditions Earth microorganisms would be expected to metabolize and reproduce. The lack of such evidence supports there being very few, if any, viable Earth microbes contaminating the biology instrument.

IV. PREPARATIONS FOR SURFACE OPERATIONS

After launch and during the voyage to Mars, the biology instrument was basically dormant. The only active elements are two mechanical thermostatically controlled heaters which maintain the LR and GEx aqueous nutrients, each contained in a sealed glass ampoule, above freezing.

During this phase of the mission all solenoid valves are open, except for two valves on the vents. The stored helium is retained in a hermetically sealed container, as are the $^{14}CO/^{14}CO_2$ for the PR experiment, the rejuvenation gas used for conditioning the gas chromatograph columns on GEx, and the $He/Kr/CO_2$ supply for GEx. A small amount of water is also stored in a sealed container in the PR experiment.

Once Mars orbit was achieved and just prior to separation from the orbiter, operating power was applied to the instrument for the first time since launch. During a 12-min sequence, preparation for landing was made. The purpose of this sequence was to close selected valves to prevent exhaust gases from the rocket engines from contaminating the instrument. In addition, the carrier gas supply downstream of the isolation valves was closed to prevent Martian CO_2 from contaminating the helium. Because of an automatic reset feature, the initial application of power automatically closes all valves except the vent valves which are opened, and turns on several heaters designed for ambient temperature control on the Martian surface. Since the heaters are not yet required, the next operation returns the instrument to the cruise condition which turns off these heaters. Specific valves are now individually commanded closed to protect the instrument from engine exhaust gases and to retain a vacuum in the CGS regulators. If the regulator system were not closed off, CO_2 would enter the regulator volumes and could later appear in the GEx analyses. All commands used for this sequence are issued from the lander guidance, control and sequencing computer.

After 3 days on the surface of Mars the biology instrument was prepared for receipt of its first soil sample.

The sequence of operations starts with the application of power to the instrument. This operation automatically closes all instrument solenoid valves, opens the valves on the vent lines, and powers the instrument ambient control heaters. Since the instrument may have been quite cold, all valve operations which would involve pressure are delayed for 100 min to allow the instrument to stabilize thermally.

The next operation is to reset by one drive operation all of the instrument's motors to their initial positions in preparation for actual cell rotations or soil distribution.

The following operations involve the accessing of the instrument's stored gases and the GEx column rejuvenative sequence. A command is given to the instrument to operate the thermal isolation valves (TIVs), which seal the GCS, etc. These valves are one-shot devices that contain oil sealed in a bellows which drives a plunger as heat is applied. When commanded, the heaters come on, expand the oil and drive a plunger through a stainless steel disc that seals the stored gases from the usage areas.

Gas rejuvenation of the GEx chromatographic column packing material is accomplished by flowing carbon dioxide and oxygen in helium through the columns. The 11-month exposure to space vacuum has depleted the packing material adsorption sites of CO_2 and O_2 and these gases are readsorbed during rejuvenation preventing the columns from later adsorbing these gases from a gas sample. A gas chromatographic run is performed to verify the column conditions and the data are stored for transmission.

The nuclear detectors are accessed to obtain a background count. Since each detector system on LR and PR contains two separate detectors, backgrounds are measured with each detector separately, and with each pair summed. This counting operation is about 6 h long in each mode.

With helium pressure available, the cells can now be positioned for acceptance of soil. This involves lowering the carousels by supplying 9.45 kg cm^{-2} helium to the vertical acutators, thereby engaging the motors and rotating the preselected cell around to each of the individual soil load ports.

Both the LR and GEx glass nutrient ampoules are broken at this time by applying 9.45 kg cm^{-2} helium to the reservoirs which actuates dual pistons (one on each end of the reservoir) and punches a hole in each end of the ampoule. The LR nutrient is degassed by flowing helium through it to remove gaseous $^{14}CO_2$ from the liquid (see Sec. V C).

The PR organic vapor trap has a tendency to adsorb some CO_2 after having been exposed to vacuum. To avoid confusing the experimental results, the OVT is exposed to the Martian atmosphere (95% CO_2) which makes the adsorbed CO_2 nonradioactive, rather than the $^{14}CO_2$ used as a tracer, which would be counted in subsequent experiment cycles.

The instrument is now ready for performance of the biology experiments, and the main operating power is turned off to allow the Viking lander batteries to charge for 5 days prior to proceeding on a full experiment cycle.

V. LABELED RELEASE EXPERIMENT

A. Labeled release experiment concept

The labeled release (LR) experiment detects biological activity in a soil by measuring the evolution of gaseous products from simple organic compounds by microorganisms.[7-9] All known terrestrial organisms metabolize carbon-based nutrients to gaseous products such as CO_2 and CH_4. In the LR experiment a simple nutrient is used which is prepared from compounds containing radioactive carbon (^{14}C). The organisms in the soil can then assimilate the compounds and give off carbon gases. The gaseous products will be radioactive and so can be detected. The gases are measured in a detector sensitive to ^{14}C beta radiation from the metabolized nutrient.

For the Viking biology instrument the LR experiment uses a small volume of nutrient compared to the soil volume (1:5 ratio). The rationale for not completely wetting the soil is to provide a moist environment (versus the pyrolytic release experiment, which is dry, and the gas exchange experiment, which is primarily very wet) and create a moisture gradient in the soil to accomodate any microorganisms with as yet unknown water requirements.

In a typical LR experiment the carbon-14 in the headspace gas is sensed. The detector counts are accumulated for a determined period of time and then the total number for that period is recorded in the data memory. The readout is then calculated as average counts per minute of the time interval of the accumulation. The LR data is accumulated continuously throughout an experiment and the data output is the number of detector counts per period throughout the experiment duration.

The variation of the carbon-14 count rate as a function of time is a measure of the activity of the soil. The probability of the presence of organisms in the soil is assessed from the total number of counts per minute evolved at long times (from 14 to 30 sols) after nutrient contacts the soil and by the rate of increase of counts with time following injection.

B. LR experiment implementation

Figure 4 is an exploded view of the LR module. The essential parts of the experiment are described below.

The head end assembly consists of an elastomeric seat to seal the test cell with an extremely low leak (5×10^{-6} std cm^3s helium) to the head end; lines from the nutrient reservoir, detector, helium gas supply, and vent; a cavity which meters 0.12 cm^3 of nutrient onto the soil; and four solenoid valves to control flow.

Four identical test cells act as containers for soil

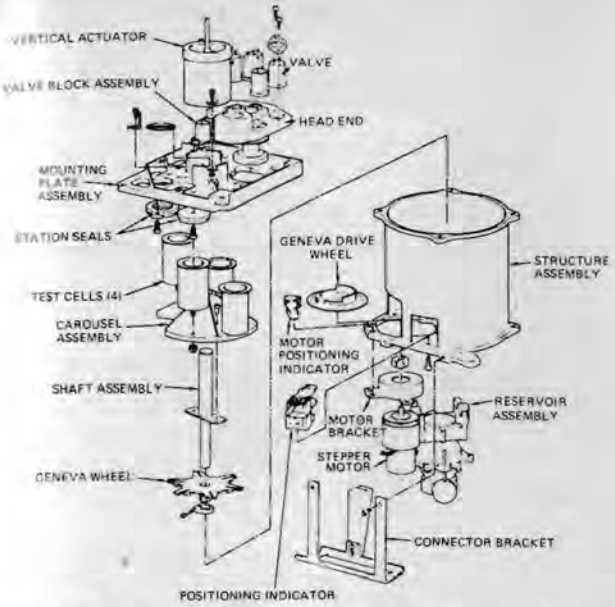

FIG. 4. Exploded view of the labeled release experiment module assembly. For clarity the liquid and gas lines which purge the test cell and supply the nutrient are not shown.

during the experiments and as dumps for excess soil thereafter. The cells are set on a Geneva wheel mechanism that is lowered to permit cell rotation and raised to seal the cells against the head end.

A dual channel solid state beta radiation detector (described in Sec. VIII C) measures the carbon-14 gases in the space above the soil.

A complex of heaters is used to sterilize the soil, as required, prevent water condensation, and heat the beta detector to remove adsorbed carbon-14 material at experiment completion.

The experiment flow diagram, Fig. 5, shows the various parts of the experiment in diagrammatic form and gives the numbering system used to denote the valves. The experiment operations are listed in Table III. The experiment operation in terms of the functions of the components is discussed below.

1. Nutrient supply and injection system

The nutrient supply function has the capability of transporting the nutrient from Earth to Mars in a sterile manner; once on the Martian surface the nutrient must be delivered to the soil in a reproducible manner while maintaining sterility.

The nutrient formulation (Table IV) was determined by G. Levin and was supplied to TRW by Biospherics, Inc. (Rockville, MD) as a deaerated solution in 25-cm^3 vials.

About 6.5 cm^3 of nutrient is required to perform four complete LR experiments on each instrument. To allow an excess, about 8 cm^3 of nutrient was placed in a Pyrex glass ampoule (Fig. 6) for each instrument.

Ampoules were filled by the following procedure designed to minimize the possibility of microbial contamination. The empty ampoules were cleaned with filtered isopropanol followed by distilled water to insure no toxic materials remained. They were then wrapped in aluminum foil and sterilized by autoclaving for 15 min. The ampoules were then filled with the carbon-14 labeled nutrient by a special apparatus which was assembled from autoclaved components in a laminar flow bench (class 100). The filling apparatus allows the nutrient to be placed in the ampoule under an atmosphere of helium which is filtered through a 0.5-μm membrane filter. The filled ampoule is sealed at 134 mbars total pressure by melting the glass fill tube. Confirmation that the ampoule and its fill-port seal are leak free is made by testing for helium leakage from the ampoule under vacuum. The sealed ampoule and nutrient are sterilized in aluminum foil by heating to 125 °C for 45 min.

Approximately 7 cm^3 of the total 8 cm^3 nutrient in the ampoule is available for injection; there is a loss of about 1.0–1.5 cm^3 from retention in the reservoir and lines and from nutrient degassing. The volume of nutrient delivered per injection is determined to be 0.12 cm^3 maximum for a bleed (discarding sufficient nutrient from the lines to assure the bulk composition being injected is that of the ampoule). Thus, for an active cycle of six bleeds and two injections, the maximum usage is 1.7 cm^3.

Adding nutrient to the soil in the test cell is accomplished by filling a closed cavity, under a pressure of 9.2 bar, with nutrient from the reservoir and then opening it to the lower pressure test cell through a line terminating in a nozzle directly above the soil sample. In order to prevent boiling of the nutrient upon injection into the Martian pressure (7.5 mbars) environment above the soil, it is necessary to admit helium to the test cell to raise the total pressure above the vapor pressure of water. Helium is added to the cell to bring the pressure in the cell to 60–70 mbars versus the water vapor pressure of 12.3 mbars at 10 °C.

2. Test cell system

The test cell is a stainless steel cylinder of 3.25-cm^3 volume with stainless flange that mates to the flat portion of the head-end assembly. There are four identical test cells which are rotated by a Geneva drive mechanism. Each test cell receives 0.5 cm^3 of soil for analysis sequence. After completion of a sequence the cell serves as a dump cavity for unwanted soil that remains in the soil distribution assembly. (The process of soil distribution is described in a later section.)

The cell mates to the head end with a Viton ring seal against a flange and is held in position by spring pressure. The cell is held in the closed position by spring tension. To lower the cell the 9.2-bar helium is applied via a solenoid valve. The cell remains depressed until the high pressure gas is vented. All rotations of the cell take place with the cell in a depressed position. (See Sec. VIII A 2 for control design.)

The portion of the head end to which the cell mates

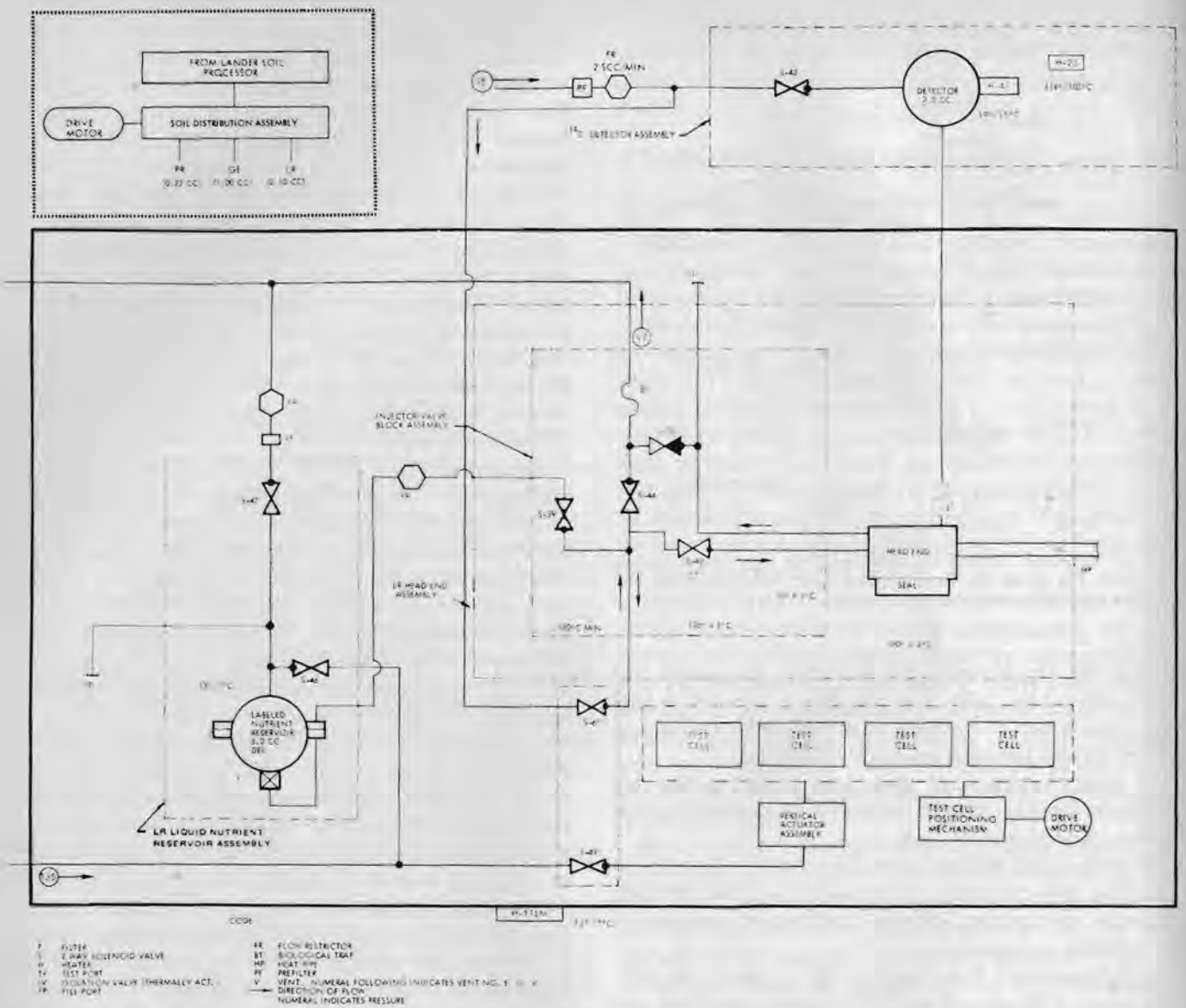

FIG. 5. Labeled release experiment module flow diagram. The module contains four test cells which receive soil and seal one at a time to the head end. The liquids and gases pass in the directions indicated through the lines and valves to inject nutrient, purge the test cell, and lower the test cells.

contains the nutrient injection port, an opening to the tube connecting the detector and cell, and an opening to a vent valve S-52.

The test cell itself has no heaters or temperature sensing equipment attached. Measurement of cell temperature and cell heating is provided by sensors and heaters in the head end.

TABLE III. Summary of the primary operations of the labeled release experiment.

Operation	*Occurrence*
1. Ampoule breakage	At initialization
2. Nutrient degassing	At initialization
3. Soil loaded to cell	Start of each experiment cycle
4. Detector background counted	Each experiment
5. Nutrient injected	Twice or more each experiment
6. Detector counts recorded	Continuously during experiment
7. Detector and cell cleanup	End each experiment

3. Carbon-14 beta detector assembly

The detector assembly consists of a 46-cm length of 0.64-cm stainless tubing connecting the head end to the detectors, the detectors consisting of two silicon diffused-junction semiconductor elements positioned to

TABLE IV. Composition of the nutrient used in the labeled release experiment. Each compound is present as $2.5 \times 10^{-4} M$ in the solution. Each nutrient injection supplies 0.12 cm^3 of the solution to the soil.

Compound	Specific activity (Ci/M)
^{14}C–formate, sodium salt	8.0 (±0.8)
^{14}C–glycine	16.0 (±1.6)
^{14}C–glycolic acid, calcium salt	16.0 (±1.6)
d–^{14}C–lactate, sodium salt	24.0 (±2.4)
l–^{14}C–lactate, sodium salt	24.0 (±2.4)
d–^{14}C–alanine	24.0 (±2.4)
l–^{14}C–alanine	24.0 (±2.4)

FIG. 6. Labeled release Pyrex glass nutrient ampoule showing the fill port extending to the lower right and the two collars surrounding the puncture discs.

monitor the trapped volume of 2.4 cm^3 between them, and associated electronics.

In any experiment the gases evolved as a result of the nutrient being dropped into the soil diffuse from the test cell down the 46-cm tube to the detector. The time for diffusion to establish 95% of equilibrium was determined to be 15 min.

The actual gases sampled by the detector chips are those in the 2.4-cm^3 volume between the detectors. The total volume of the cell plus tubing and detector was 8.95 cm^3, of which 8.60 cm^3 was head space when 0.5 cm^3 of soil was added with 50% solid volume. The detector counting efficiency is 10.9% for the gas directly in the detector volume. These combined to give an overall system efficiency of 3% for detection of carbon-14 over the entire head space.

The output of the two detector elements is normally summed electronically, and the total output accumulated by a register. However, if one detector fails, the data from the other detector can be accumulated separately.

4. *Module thermal control*

The central section of the LR module proper is heated by the module enclosure heaters. These are 9-W heaters that maintain the test cell temperature at its minimum operating temperature of 8°–10 °C. These heaters also serve to maintain the temperatures of lines and the nutrient in the reservoir. At temperatures above 15 °C thermoelectric coolers are activated that maintain the cell temperature below 25 °C.

The beta detector is equipped with a heater that cycles on at 15 °C and off at 19 °C, thus maintaining the detector temperature at a level above that of the cell. This temperature differential is important to guarantee that water will not be condensed (changing the effective dissolved nutrient concentration at the soil) in the detector or detector line. Above 15 °C environment the detector assumes ambient temperature.

The detector is not controlled by the thermoelectric coolers and its temperature can rise above 27 °C. The detectors have been tested at the component level and found to be essentially noise free up to 50 °C allowing them to operate satisfactorily without cooling.

The soil in a control experiment must be heat sterilized to destroy any organisms initially present in the soil. The sterilization method was heating at 160 °C or greater for 3 h. The LR cell heater is located at the head end flange and serves to heat the head end and the test cell through the flange coupling. Experimental data show that heating the head end flange to about 190 °C results in a nominal heating at the test cell bottom of 160 °C. The LR head end is also heated to maintain the sterility of head end parts. In this case the head end flange heater is used as the main heating element.

The LR detectors are heated during the sterilization cycle to prevent condensation of any outgassed material on the detector. Heaters on the detector mounting plate raise the detector body temperature to 110 °C.

C. LR experimental operation

During the initial sequence conducted after landing on Mars, one of the first operations to be performed in the LR experiment is breakage of the nutrient ampoule. The ampoule is punctured at the top and bottom by pistons which pierce break-disks set in reinforced glass rings at each end of the ampoule. The pistons are driven by 9.2-bar helium when valve S-46 (Fig. 5) from the high-pressure helium regulator is opened. This lower piston is equipped with a flow path that allows nutrient to flow from the reservoir to a nutrient line that connects the reservoir to valve S-59 at the head end assembly.

Following the puncture of the ampoule, the high-pressure helium serves to drive the nutrient from the reservoir to the head end. The initial helium is vented from the reservoir during the nutrient degassing (see below). Each time an injection of nutrient is required, S-46 is opened and the reservoir pressurized. Following the initial pressurization the 9.2-bar helium remains above the nutrient (Fig. 5). While injection of nutrient does not significantly deplete the helium pressure, the reservoir is repressurized prior to each injection sequence as a safeguard against possible leakage.

The LR nutrient is labeled with carbon-14, and undergoes time-dependent radiolytic decomposition. This decomposition is normally a slow process and the nutrient components are stable for long periods. However, upon heating the rate of thermal decomposition increases, producing a considerable radioactive background due to the production of volatile material. This background will appear as carbon-14 in the beta detector after nutrient is placed on the soil. The instrument underwent two sterilizations—a 54-h sterilization at 120 °C at TRW and a 112 °C sterilization at Kennedy Space Center of 26 h, prior to launch. These

sterilizations heat the nutrient and the radioactive gas generated must be removed before the first experiment.

To remove the radioactive gases helium is bubbled through the nutrient. This occurs immediately following the ampoule breakage 2–3 days after landing on the Martian surface. The high-pressure helium in the reservoir is first vented through S-47 (Fig. 5). Helium at 1.2 bar is then flowed through the nutrient through S-61 and S-59.

The flow is 2 std cm^3/min controlled by restrictor FR-4. A second restrictor, FR-3, at the reservoir creates a back pressure in the reservoir of about 200 mbars to control the flow of helium and maintain the pressure above the water boiling point. The flow continues for 5 h, corresponding to a flow of 600 std cm^3 of helium. Tests have shown that this procedure reduces the background radioactive gas to a level that does not contribute significantly to the instrumental background. The amount of water lost from the nutrient during degassing is less than 0.1 cm^3. The nutrient is degassed only once. Valve S-47 is not used again. This guards against possible nutrient microbial contamination from Martian organisms residing in the vent system.

Nutrient is injected onto the soil by filling the cavity formed by valves S-44, S-45, S-59, and S-61 (Fig. 5) with nutrient from the reservoir utilizing valve S-59. The cavity is first filled with 1.26 kg cm^{-2} helium through valve S-61 to prevent the high-pressure nutrient (9.2 bars) from forcing open a valve due to its hammering effect. A line-bleeding operation to provide unheated nutrient for the injection is performed by twice emptying the filled nutrient cavity to vent through S-44 and then filling it a third time and admitting this volume to the test cell through S-45.

The test cell pressurization prior to nutrient injection is accomplished by filling the nutrient cavity with helium at 1.2 bars through S-61 (the nutrient having been vented through S-44) and twice admitting the helium to the test cell through S-45. Each helium admission raises the cell pressure by approximately 30 mbars. This pressurization plus the Martian ambient pressure of 7.5 mbars brings the cell pressure at the time of nutrient injection to 60–70 mbars.

Nutrient injection is programmed to occur at the same time of the Martian day for each experiment cycle to assure nutrient volume reproducibility by reproducing the thermal environment as closely as possible for each injection. Following nutrient injection, no operations are conducted in the experiment until its termination. Data are collected from the carbon-14 detectors but no other activity occurs. In order to accurately describe the rate of carbon-14 release immediately after injection, the number of counts accumulated by the detector is recorded once every 4 min for 2 h and then once every 16 min for the remainder of the experiment cycle.

More than one nutrient injection (0.12 cm^3) can be conducted on one soil sample to increase the available nutrient quantity at a selected time within the incubation sequence. When this is done, the standard nutrient injection sequence is repeated minus the helium pressurization of the test cell.

After an experiment is completed the cell containing the tested soil is rotated from the head end and an empty cell is emplaced at the head end. The detector and head end system is then cleaned using the cell flange heater and the detector heater. During the cleanup, helium is flowed through the system to carry evolved carbon-14 out of the LR detector-cell-head space and to the vent. To accomplish this, a stream of helium enters at the detector (valve S-42) at 2-cm^3/min and is vented at valve S-42. The length of detector and cell heating has been selected so that the adsorbed radioactivity at the head end will be removed and the detector carbon-14 background reduced prior to the next experiment. The temperature of 110 °C at the detector and 170 °C at the head end is sufficient to remove most of the adsorbed radioactivity.

The vent lines through which the purged gases flow (V-2, Fig. 5) are heated to about 40 °C by H-24 GG during the cleanup. This temperature is used during all operations using the vent system and prevents the condensation of volatile material in the vent during the cleanup. The vent heaters are turned on 30 min prior to the operation and operated continuously until 30 min following the operation.

D. LR experiment sequence

The major elements of one cycle of the experiment are receipt of soil, detector background determination, initial and additional nutrient injections, experiment termination in preparation for the next experiment and the optional sterilization of the soil for a control analysis. A block diagram of the sequence steps is presented in Fig. 7 showing the soil sterilization option as a branch to the primary sequence. Each major sequence function consists of the activities listed under the functional blocks.

A test was performed on Earth according to the sequence outlined in Fig. 7 using an instrument nearly identical to the ones landed on Mars. In order to simulate operation on the Martian surface, the instrument was operated in an environmental control chamber at a pressure of 5.3-mbar CO_2 and in a thermally controlled shroud which mimicked the expected diurnal temperature variation within the lander (0°–28 °C). The data from the carbon-14 detector in the LR experiment are given in Fig. 8 for that test. The test sequence consisted of two cycles: an active and a control on sterilized soil.

The soil used in this test is a red podzolic, Aiken series, collected in a wooded area near Placerville, CA. The soil had been air dried and stored for 9 years in a screw cap glass jar in the dark at ambient temperature in Mountain View, CA. Microbial analyses indicated 3×10^5 to 2×10^6 aerobic organisms, approximately 6×10^4 anaerobic organisms, and 3×10^3 algae per gram of dry soil. The soil was exposed to

the 5.3-mbar CO_2 atmosphere of the test chamber for about 2 h before beginning the sequence of Fig. 7. Prior to the test, the entire biology instrument had been sterilized at 112°C for 40 h so that all biologically related experiment response is due only to organisms from the soil sample.

The test results (Fig. 8) illustrate the carbon-14 release from an active soil and from another sample of the same soil after heat treatment at 160°C for 3 h. Each point on the plot is a recorded carbon-14 detector measurement. The sharp rise in volatile carbon-14 immediately upon nutrient injection is obvious in both the active and control plots. The difference between the two is that the active plot continues its rise for a longer period and reaches a significantly higher value. The difference of 1.5 orders of magnitude at the highest level in each case is ascribed to biological activity in the test soil.

The data are presented in cpm and can be converted to dpm using an overall detector efficiency of 3%. The dips in the otherwise well-behaved data are caused by purposely exercising the instrument's capability to use only one of the two sensing elements in the carbon-14 detector—giving a drop to one half the normal value in each case.

The two biology instruments have successfully executed 8 sequences on the Martian surface. Table V lists those sequences and gives the time for the major events in each. Seventeen nutrient injections have been performed and carbon-14 release data recorded for a total of 6560 h following those injections. For each experiment in Table V, background detector data was recorded from the time of soil receipt until the first nutrient injection.

The data interpretation from the Mars surface operations has been discussed elsewhere.[18,19]

VI. PYROLYTIC RELEASE EXPERIMENT

A. Experiment concept

The pyrolytic release (PR) experiment is designed to search for life on the basis of a common property of living organisms, namely, that they incorporate CO_2 or CO into higher organic compounds.[5,6] In particular, this experiment is designed to detect carbon assimilation by organisms in Martian soil under conditions altered as little as possible from the natural Martian environment.

In order to detect the incorporation of either CO_2 or CO, the natural Martian atmosphere above the soil which contains both these gases is supplemented with trace amounts of ^{14}CO and $^{14}CO_2$. On Earth, this assimilation process is enhanced by the addition of water vapor and/or simulated sunlight, and as both of these are present on Mars, this capability is part of the experimental hardware. However, the ultraviolet component of the sunlight is removed to eliminate the possibility of nonbiological formation of organic compounds.[20,21] The Martian soil is exposed to these condi-

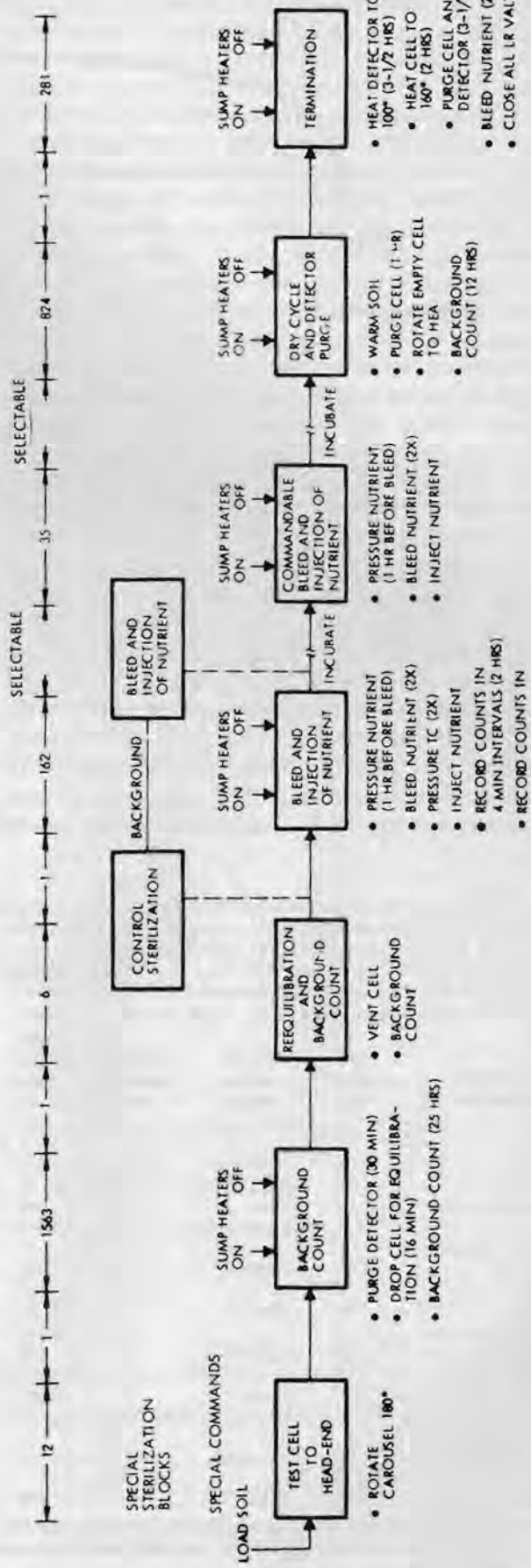

FIG. 7. Labeled release experiment sequence diagramming the major events and operations as blocks against a typical sequence.

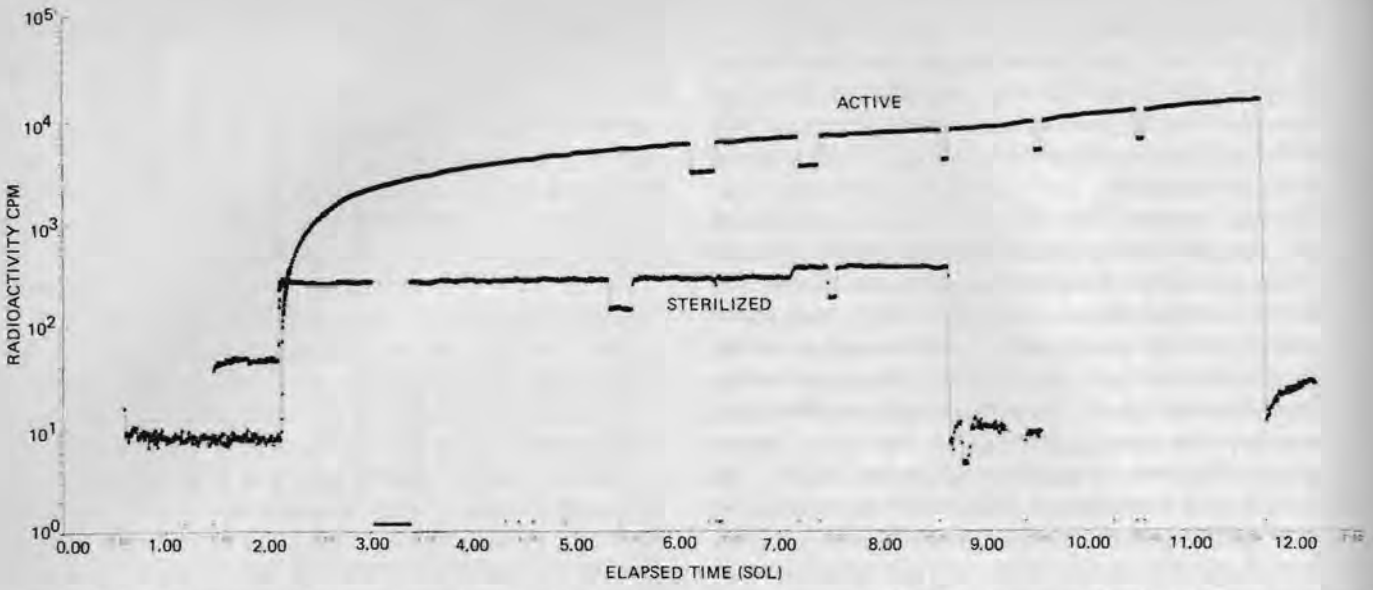

FIG. 8. Labeled release experiment active and sterilized soil carbon-14 release from test of flightlike instrument. Each of the two experiment sequences consists of a background segment, two nutrient injections, and carbon-14 gas purge and subsequent background. The data sections where the count rate is one-half the normal rate are caused by purposely recording only one of the two halves of the beta detector.

tions for about 120 h and then the radioactive atmosphere above the soil is removed and the soil is pyrolyzed in a stream of helium gas. The organic matter including the newly synthesized radioactive material in the soil is volatized by the pyrolysis and is transported into an organic vapor trap (OVT) by helium carrier gas where it condenses. Any residual $^{14}CO_2$ and ^{14}CO from the incubation atmosphere or any generated during pyrolysis of the soil passes through the trap and is collected in a solid-state counter where it is detected by the beta decay of the ^{14}C atoms (see Sec. VI C 2).

The amount of radioactive organic material contained in the vapor trap is obtained by first heating the vapor trap to 625 °C in a stream of helium. This heating breaks down the organic material into gaseous radioactive oxides of carbon, and these are again carried into the solid-state detector and counted. This second radioactive count provides a measurement of the amount of radioactive carbon that was assimilated by the organisms in the original soil incubation. The first radioactive count provides an estimate of the size of the error in the second "organic" count that could be attributed to $^{14}CO_2$ and ^{14}CO that had been adsorbed on the OVT based upon a prior calibration.

A second duplicate experiment can be performed as a control except that a sample of the same soil is sterilized prior to exposure to the incubation gases. This control experiment provides information as to the size of the radioactive "organic" synthesis by the Martian soil and the background of the experiment hardware after heat inactivation of any Martian microorganisms.

The PR experiment provides a method of determining if carbon assimilating microorganisms exist in the Martian soil without subjecting them to abnormal Martian conditions. The Martian soil is exposed to no conditions or environments which are different from usual Mars conditions except a higher temperature for the incubation.

TABLE V. Labeled release experiment summary of Mars surface operations. Each experiment sequence is described by the Viking mission time for start and stop and the experiment identifying characteristics. Sols are the number of Mars days elapsed since landing. Sol 0 is July 20, 1976 for Lander 1 and September 3, 1976 for Lander 2.

Experiment description	Soil received, sol	Sterilization regime	Nutrient injections, number	End experiment, sol
Lander 1				
Active	8	None	2	23
Control	24	3 h, 160°C	2	37
Extended active	38	None	3	89
End of primary mission				
Double nutrient active	230	None	2	306
Lander 2				
Active	8	None	2	24
Low temperature control	28	3 h, 50°C	2	48
Active, subrock soil	51	None	2	141
End of primary mission				
Low temperature control repeat	145	3 h, 50°C	2	171
High soil ratio, active	None[a]	None	1	260

[a] Experiment sequence begun on Sol 225 with previously dumped soil residing in the cell.

B. PR experiment implementation

A metered amount of soil (0.25 cm^3) is dropped into a selected PR test cell by the SDA. The pyrolysis experiment contains a carousel that holds three test cells and three dump cells (Fig. 9). Each of these test

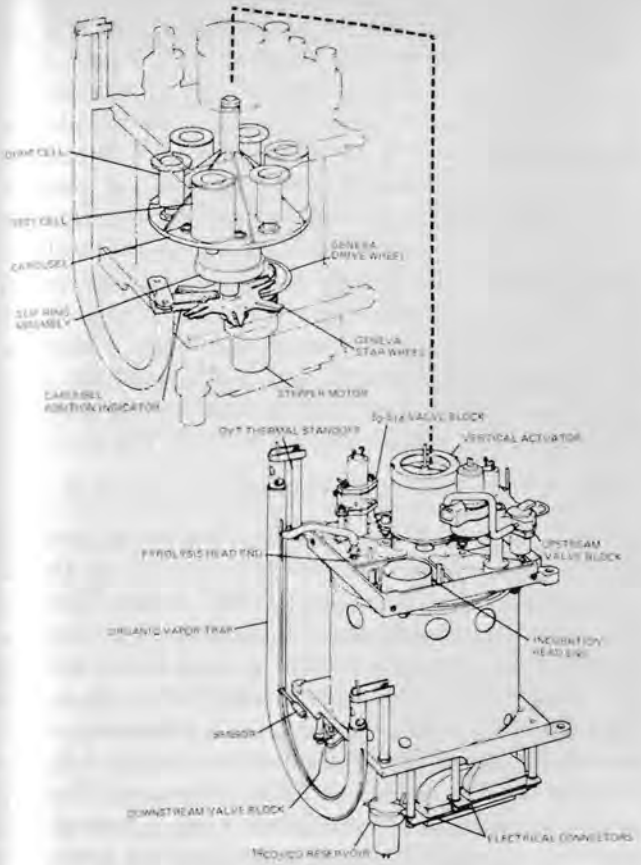

FIG. 9. Exploded view of the pyrolytic release experiment module assembly. For clarity the liqud and gas lines which supply the helium flow, $^{14}CO_2/^{14}CO$ incubation gas and water vapor are not shown.

cells can be indexed under the soil loader port. This design allows test cells to receive a calibrated soil sample and the dump cells can be used to empty the soil hopper in preparation for the arrival of a new soil. Once loaded, the incubation cell is moved through 180° (by three steps of a six position Geneva mechanism) to the incubation station. This operation places a dump cell under the load port so that soil can be emptied from the metering cavity into the cell. It also places a clean dump cell under the pyrolysis head end so that presoil analysis procedures can be performed at the pyrolysis station. At the end of the soil incubation, the soil is moved to the pyrolysis station for the pyrolysis of the soil, after which the carousel is again rotated so that the clean dump cell is replaced under the pyrolysis head end. This operation provides a soil-free flow path for the final determination of the level of radioactive organic material at the pyrolysis position.

Prior to the start of another experiment, the carousel is again rotated so that a new test cell is placed under the soil loading port and the same experimental sequence is repeated. The experimental sequence is arranged so that the dump cells that receive soil are not used under the pyrolysis head end for pre- and final analysis procedures.

The flow diagram for the pyrolytic experiment is shown in Fig. 10. The first operations occur at the incubation station, which contains all the systems that are required to perform a natural Martian soil incubation. Each of these systems is physically con-

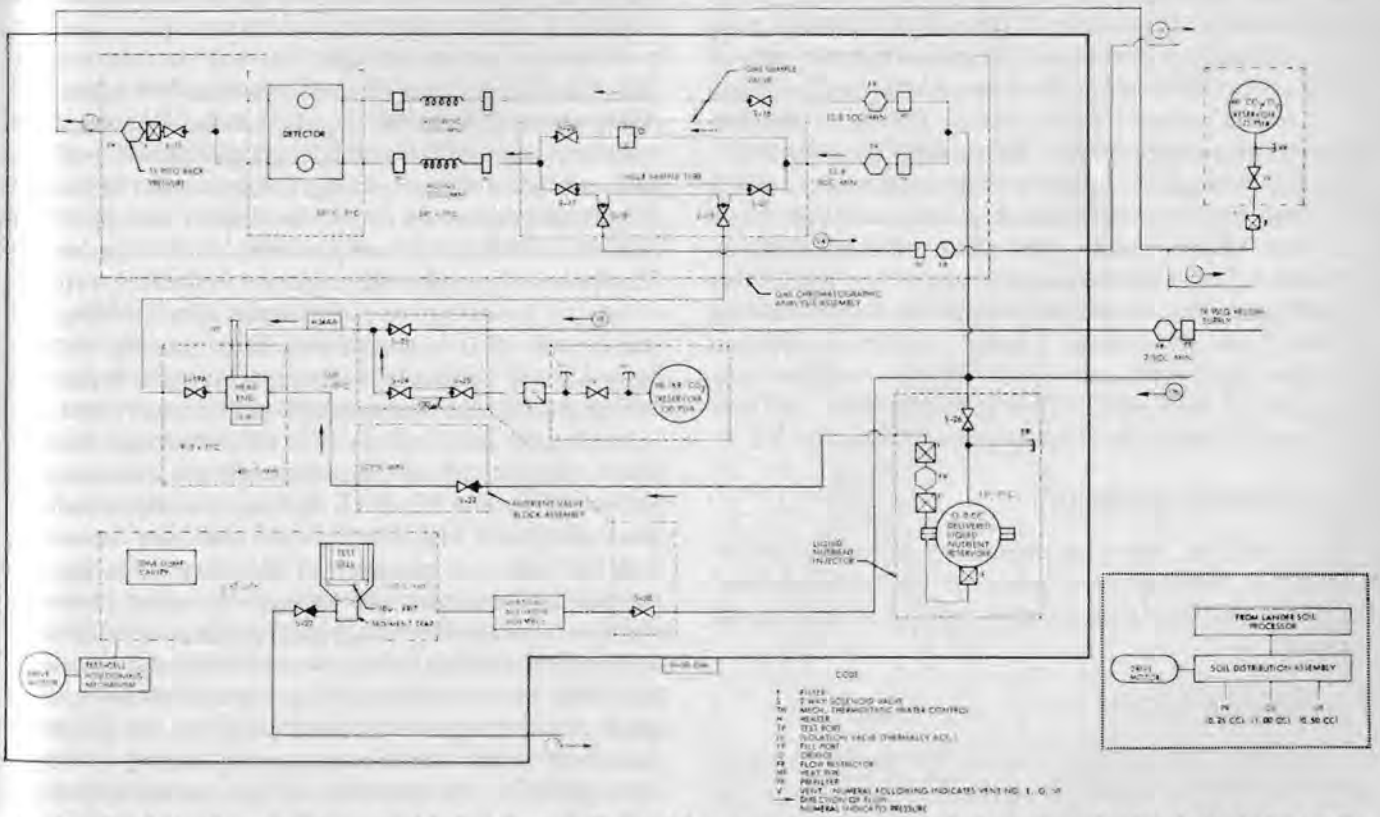

FIG. 10. Pyrolytic release experiment module flow diagram. The module contains three test cells which receive soil and seal one at a time at the incubation head end and the pyrolysis head end in that order. The gases and water vapor flow through the lines in the directions indicated to carry out the incubation and analysis cycle operations.

nected to the incubation cell via the incubation head end assembly. The incubation volume formed when the cell is sealed under the head end is made leaktight by compressing the test cell containing soil against an elastomeric seal in the incubation head end. A controlled amount of $^{14}CO_2$ and ^{14}CO (tracer gases) is injected into the cell by initially allowing the incubation gases to flow from a reservoir into a calibrated volume. The gas is expanded from this volume into the incubation cell which contains the soil and the normal Martian atmosphere. If humidification of the incubation cell is required, the valve between the water vapor reservoir and the incubation cell is opened for a predetermined time period that allows a capillary-controlled flow of water vapor to enter the cell. If simulated sunlight is required, the xenon arc lamp is used to illuminate the soil through an optical window in the incubation head end. During the incubation, the cell temperature is kept within a predetermined range by automatic operation of heaters and thermal electric coolers. At the end of the incubation period, the incubation gases are allowed to diffuse out of the incubation cell by opening valve S-12 that connects the cell to instrument vent line V4.

The incubation cell is then moved to its second position, the pyrolysis station. Here the pyrolysis head end and the test cell form a programmable pyrolysis oven that is constantly purged with a 1.5-cm^3/min helium gas flow. This helium carrier gas flow removes the pyrolysis products from the cell and carries them into an organic vapor trap. The trap is a temperature programmable 25-cm-long, 0.3-cm-diam stainless steel tube containing a mixture of Chromosorb P and copper oxide. The Chromosorb provides a large surface area for trapping organic condensation products and the copper oxide, when heated above 500 °C, oxidizes the organics to oxides of carbon. The helium gas exiting the trap can be either directed into an instrument vent line (V1) or into a solid-state radiation detector assembly. This temperature programmable detector assembly contains an isolable spherical 6-cm^3 holding chamber and an isolable 1.4-cm^3 cylindrical detector volume. Both the end faces of the cylinder are composed of solid-state silicon beta detectors. The exit line from the detector cylinder goes to vent line V1.

C. Experiment operation

Operation of the experiment is described below through a detailed description of the construction, purpose, and function of each of the critical components.

1. Incubation System

Test cells. The six cells mounted on the PR carousel are all made of 316 stainless steel. Three of these cells are used as test cells which have an internal volume of 2.6 cm^3, while the other three are dump cells and have an internal volume of 2.95 cm^3. The total incubation system volume, which is composed of the test cell and the incubation head end volume, is 4.13 cm^3. Each test cell has an integral heater and a temperature sensor which provide five temperature set points. The first set point is (85° ± 10°)C which is used to heat the soil prior to sterilization. The second set point is (115° ± 10°)C which is used to heat the soil after the incubation to remove the gases adsorbed on the soil during incubation. This heating is carried out with the cell exit valve, S-12, open which allows any water in the soil to evaporate. This ensures that when a sterilization is performed at 160 °C, with S-12 closed, the pressure produced by superheated water vapor does not overcome the pneumatic helium pressure that holds the cell closed. The third set point of $160^{\circ}\ ^{+20}_{-0}$ °C is to sterilize the soil with dry heat. The fourth set point is (625° ± 25°)C which is used during soil pyrolysis. During this operation the cell reaches 625 °C in less than 90 s and holds this temperature for another 90 s. This ensures that any organics present in the soil are released as volatiles over a very short time period, at a time when the temperature of the cell is a maximum, which reduces the possibility of condensation in the cell. The final temperature of (725° ± 25°)C is used only if a soil sample needs to be repyrolyzed after a normal soil analysis procedure. This operation is carried out so that a new experiment can be performed with another soil placed on top of the pyrolyzed soil. Earlier experiments have shown that this "over pyrolysis" procedure removes the majority of the carbon-14 material that appears in a subsequent pyrolysis.

To ensure that a minimum of heat is lost from the cell, especially during the fast heating phases, the test cell is encased in a stainless-steel jacket which acts as a thermal standoff. The thickness of the cell wall decreases toward the cell sealing flange in order to protect the elastomeric seals in the incubation and pyrolysis head ends during high-temperature cell heating cycles. The three dump cells, which cannot be heated, provide a capacity for accepting soil samples when loading soil into a test cell is not desired. They provide a clean flowpath for sealing the analysis system head end during the organic elution phase of the experiment.

Incubation gas reservoir. The incubation gas is composed of a mixture whose composition is calculated to be 94% $^{14}CO_2$ and 6% ^{14}CO. It is injected into the head space above the soil from a 2-cm^3 reservoir containing 2 mCi of gas at a pressure of 535 mbars. During the journey to Mars, the reservoir is sealed with a piercable stainless steel membrane. Upon landing, an initialization sequence is performed in which the membrane is punctured by a thermally driven piston. The incubation gas is injected into the incubation cell by the following procedure (Fig. 10): the miniature latching solenoid valve (MLSV) on reservoir S-5 is opened, allowing the calibrated 20-μl volume between S-5 and S-6, which is at Martian pressure, to be filled with radioactive gas. Then S-5 is closed and S-6 is opened, allowing the

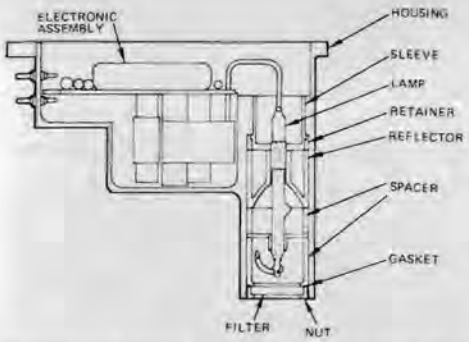

FIG. 11. Pyrolytic release experiment xenon arc lamp illuminator assembly. The arc lamp illumination is focused through the filter by the reflector and reaches the soil through a quartz window above the test cell.

incubation gas to diffuse into the incubation cell. A single injection of incubation gas introduces approximately 20 μCi (4×10^7 dpm) and an overpressure of about 2.5 mbars into the test cell. The resulting test cell pressure during the incubation will be Martian ambient (7.7 mbars at landing with diurnal and long term variation[24,25]) plus the 2.5 mbars of ^{14}C gas.

Water reservoir. The PR water reservoir has a total volume of 2 cm^3 and is loaded with a nominal 0.5 ml of water. Prior to sealing on Earth, a thorough degassing of the water by repeated freeze-evacuate-thaw cycles was performed to remove any trace of air. Then it was sealed with an isolation valve until punctured on Mars during the initialization procedure. Once the instrument receives power, the reservoir and associated valves and tubing are maintained at (30° ± 1°)C at all times. This ensures that the reservoir is always hotter than the test cell which produces a pressure differential between the reservoir and the test cell. The water vapor injection into the incubation cell is initiated by opening valve S-7. The amount of water vapor injected is controlled by a flow restrictor and the time period that S-7 is open which can be varied in multiples of 1 min. A 1-min injection was used which provides enough water vapor to saturate the test cell atmosphere when the cell is at about 24 °C.

PR lamp. The incubation head end (Fig. 9) contains a quartz window through which simulated Martian sunlight can irradiate the soil in the test cell. This artificial sunlight is provided by a xenon arc lamp (Fig. 11) assembly with a spectral range and distribution that is very similar to Martian sunlight (Fig. 12). The system requirement was that the artificial light must approach Martian solar radiation in intensity and spectral distribution. More specifically, it is necessary to provide 10%–120% of the Martian solar constant over the spectral range of 335–400 nm and 15%–120% of the Martian solar constant over the spectral range of 400–1000 nm. Furthermore, radiation between 335 and 400 nm must contain no energy from spectral lines that exceeds the ambient Martian solar intensity by 20%. Radiation below 320 nm was purposely excluded to reduce the possibility of nonbiological formation of organic compounds by a surface catalyzed photoreduction of CO.[20]

Ultraviolet wavelengths below 320 nm were reduced to less than 0.5% and the spectral shaping between 335 and 400 nm achieved by a Schott WG335 filter. The xenon spectral deviation from the solar spectrum in the infrared region is eliminated with the use of filters. The total lamp intensity is about 20% of the maximum Martian solar irradiation from 335 to 1000 nm.

The lamp is started by a 7.5-kV pulse and sustained by a 12-V, 0.5-A power supply. The lamp output power is controlled and it operates at an average power consumption of 6 W. During incubation, the lamp supply current is monitored once every 32 min. If the lamp is found to be extinguished, a series of eight start pulses is sent. However, if the lamp does not start at this time, another set of restart pulses is sent again 32 min later when lamp current is checked.

2. Analysis system

Organic vapor trap. The OVT is essentially a high-surface-area condensation trap coupled with high-temperature oxidation capability. It is a J-shaped stainless steel tube, about 25 cm long and 0.25 cm i.d. A Calrod heater runs axially through the tube that is packed with Chromosorb P coated with 25% by weight of cupric oxide. The ends of the tube are stopped with stainless steel frits which permit the flow of gas but which retain the packing material. The packed stainless steel tube is surrounded by a 0.8-cm-diam outer gold-plated tube to reduce radiation losses. The inner tube has a platinum resistance sensor mounted at a point midway from either end. This sensor provides housekeeping data and allows for heater control. The OVT has two temperature set points of (120° ± 10°)C and (625° ± 25°)C.

The packing material in the OVT provides a large surface area for the condensation of organic material. However, this packing material is the major adsorber of the radioactive oxides of carbon released from the soil during pyrolysis. This adsorbed gas is the major source of error in the experiment as it is impossible

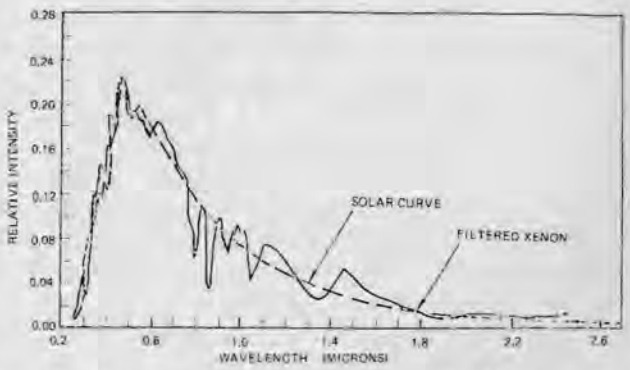

FIG. 12. Xenon-arc lamp spectrum versus the Martian surface solar illumination. The xenon-arc lamp spectrum is that which is generated by the flight configured illuminator including the filters. The intensities are normalized to their maximum output at corresponding wavelengths. The light intensity actually reaching the soil in the test cell is about 20% of the Martian surface maximum at the subsolar point.

to distinguish this gas from the organics that are converted to oxides of carbon during the subsequent elution heating of the OVT. Therefore, a substantial design and laboratory effort was made to reduce the adsorption to a minimum. All metal surfaces were thoroughly cleaned and all interior materials were selected for their low oxide of carbon adsorption coefficients. During pyrolysis, the OVT is heated to 120 °C to reduce adsorption of these gases with the associated risk of the loss of some organics which will not condense out on the OVT at this elevated temperature. These procedures produce an OVT adsorption level of only one part in ten thousand ($1:10^4$). This value was an average obtained for measurements carried out on six flight quality traps. This means that if a soil pyrolysis produces a count of 10^6 dpm, the resultant organic peak will produce $\sim 10^2$ dpm from OVT adsorption of oxide of carbon gases that were released during pyrolysis.

During the elution cycle, the OVT is heated to 625 °C in a period of 90 s. A temperature above 500 °C was required for cupric oxide to act as a strong oxidizing agent. Temperatures much higher than 625 °C cause a deterioration of the packing material which increases the adsorption of the oxide of carbon gases. The fast rate of temperature increase produces a maximum in organic oxidation products. Also it minimizes the amount of carrier gas required to transport the products into the detector.

Pyrolysis head end. The temperature requirements of the pyrolysis cell head end and line to the OVT made the design of this system difficult. To prevent organic condensation it is necessary to keep the head end and line at approximately 200 °C during pyrolysis. However, the head end seal should not exceed its maximum specified temperature of 265 °C when the pyrolysis test cell compressed against this seal reaches 625 °C. The selected heater for H-22 (Fig. 10) is a metallic sheath design that operates in series with the H-22 AA line heater. The line junction between the head end and H-22 AA is maintained at the required temperature by a coating of aluminized Kapton secured with gold tape.

Thermal control of the PR module. The thermal environment provided by the lander and the instrument is supplemented by a variety of heaters and coolers. The normal PR module thermal environment is maintained by heater H-11 PM, which is positioned on the stainless steel can surrounding the module.

To provide control of the incubation temperature during warm periods within the lander, two thermoelectric coolers are connected through heat pipes to the incubation head end (Fig. 13). These coolers dissipate the heat generated when the lamp is on and cool the head end as the instrument warms during the Martian day. Under simulated "warm" (versus cold or hot) Martian conditions, the incubation head end temperature range is 0°–11 °C while the instrument undergoes a −5° to 28 °C temperature variation. This ensures that any water present in the cell does not freeze and

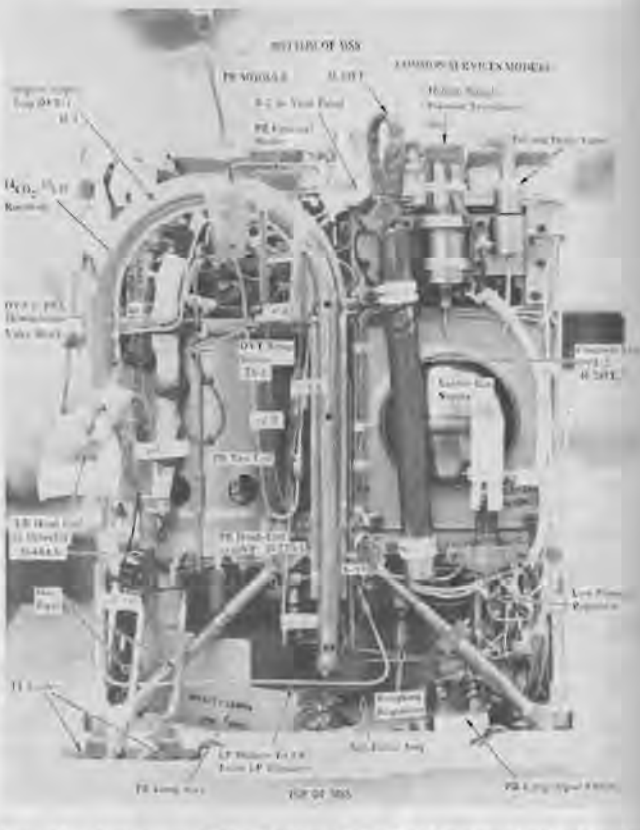

FIG. 13. Side view of the biology instrument mechanical subsystem showing the pyrolytic release module on the left and the common services module on the right. The inverted U-tube in the pyrolytic release module is the organic vapor trap.

minimizes the temperature variation to which any organisms are exposed.

Detector. The PR detector consists of two silicon diffused-junction semiconductor chips that are arranged to efficiently monitor a trapped volume between them. The function of the detector is to measure the number of beta particles produced in the trapped volume from the decay of ^{14}C which has a mean energy of 155 keV. This measurement has to be performed on Mars in the presence of a fairly high level of relatively low-energy radiation from the radioisotope thermoelectric generators on the lander and a flux of high-energy cosmic rays. The thickness of the detectors and electronic discrimination circuitry is preferentially optimized to detect the ^{14}C beta particles. The output of the two detectors is normally summed electronically and the total output accumulated in a register. However, if one detector fails or becomes electrically noisy, the other detector can be commanded to operate separately.

The PR detector trapped volume is 1.4 cm^3 and the detector system has an overall counting efficiency of 10.94%. This volume was selected for efficient counting of the oxides of carbon produced during the OVT heating cycle. The pyrolysis cycle produces approximately five times as much gas as the elution cycle but it normally contains several orders of magnitude more radioactivity. As the pyrolysis count is not as important as the elution count, it does not need to be counted as accurately. In order to obtain an adequate estimate

of the radioactivity produced in the pyrolysis cycle, a 6-cm³ holding chamber is included as an integral part of the detector assembly to trap the entire first peak. Only 20% of the total volume of the gases at equilibrium in the holding chamber is placed in the detector volume for counting. Under these circumstances, the counting efficiency for the first peak is 2.64% (average for six flight detector assemblies). In order to decrease the possibility of adsorption of the oxides of carbon in the detector chamber, the interior of the chamber is gold plated and each silicon detector chip is brazed directly onto the detector chamber. As adsorption is a function of both the level of radioactivity to which the material is exposed and the time of exposure, care is taken to minimize the counting period of any large amount of radioactivity. The pyrolysis peak is counted for only 16 1-min count periods and is then vented.

The detector assembly is equipped with a heater (H-23) which can heat and maintain the detector assembly at (109° ± 5°)C. In the normal sequence, the detector is heated for 120 min at (109° ± 5°)C after the pyrolysis count period, to ensure a high efficiency for desorption of the oxides of carbon from the system.

3. Experiment data

Data counting requirements. The PR criterion for detecting the amount of metabolic activity in a soil sample is based on the comparative size of the organic (second) ^{14}C peak from an "active" and from a sterilized soil sample. The organic peak is determined by trapping the effluent from a 625 °C heating of the OVT in the detector chamber and counting the resultant radioactive oxides of carbon for many hours. In order to monitor the movement of carbon-14 material in the experiment, several additional but separate radioactive counting periods are required during the experiment. These additional count periods provide information on the PR system "background" processes that could influence the size of the second peak.

The interpretation of the experiment data requires that the second peak count can determine 100 dpm of ^{14}C as a 3σ increase above background, so it will need to be counted for a time period equal to

$$t = \frac{(3)^2 \times \text{background count rate}}{(\text{detector counting efficiency})^2}. \qquad (1)$$

The background count rate is dependent on several processes, but the largest contributor to this background count is produced by secondary electrons resulting from neutron emission from the plutonium in the radioisotope thermoelectric generators (RTG) that provide power for the lander. The best estimate based on testing with non-Viking RTGs of the magnitude of this radioactive background was 1360 cpm and based on Eq. (1) the second peak would need to be counted for 102 min to determine 100 dpm. In addition to the RTG background, other background sources include cosmic and galactic radiation and radioactive decay processes associated with the magnesium–thorium (MgTh) alloys used in the construction of several lander science instruments including biology. These additional radiation sources were expected to provide an increase of about 30% to the RTG background. Because of uncertainty in the background due to increased radiation with RTG fuel age and impurity level, a count period of 8 h minimum was selected to provide adequate statistical margin. In order to assess the constancy of the count rate, this count period needed to be divided into a number of subintervals so that a χ-square test could be performed. The length of each individual count interval was 16 min. Therefore, the 8-h count period provides 30 subintervals of counting and based on statistical considerations, allows a χ-squared interpretation of the data to be made.

Another possible source of error in the second peak ^{14}C count rate is associated with the effect of temperature on the silicon detectors. The detector noise (N_d) due to these thermal effects is equal to $[(N_t)^2 - (N_n)^2]^{1/2}$, where N_d is the detector noise in keV full-width at half-maximum (FWHM), N_t is the total noise in keV FWHM, and N_n is the electronic system noise in keV FWHM. This detector noise varies in a manner described by $N_d = Ae^{T/T_0}$, where A and T_0 are constants [$A = 0.461$ and $T_0 = 27.22$]. Based upon the lower discrimination level applied to the silicon detectors (30 keV), the total noise should not exceed 10.7 keV FWHH at 20 °C. This figure was based upon a specification of 7.1 keV for the detector and 8.0 keV for the charge amplifier (FWHM). Testing of the detectors eventually used on Mars indicated the noise requirement could be met at temperatures up to 50 °C.

Based upon statistical arguments, a background count with no ^{14}C present was carried out for a time period equivalent to the length of the organic peak count and was carried out both before and after the critical organic peak count.

The other important count period is associated with the measurement of the radioactive products from a soil pyrolysis. The OVT adsorbs small quantities of the oxides of ^{14}C as well as acting as a condensation trap for organics. It is not possible to differentiate between the adsorbed oxides of ^{14}C and those produced from organics during the OVT heating to 625 °C. It is important to obtain a measure of the amount of oxides of ^{14}C that have passed through the OVT to provide a direct indication of the amount adsorbed by the OVT (normally $1:10^4$ parts are adsorbed). From earth tests the size of the pyrolysis peak was judged to be 10^4 to 10^6 dpm. With this magnitude of signal, the count period can be substantially shorter. As a result of the large amount of gas generated during the pyrolysis sequence, a holding chamber is used, the additional volume of this chamber reduces the overall efficiency of the detection system to (2.64 ± 0.33)%, from the (10.94 ± 1.16)% for the detector alone. With this detector efficiency, a first peak of 10^4 dpm is equivalent

to a count of 264 cpm. Assuming equal counting times for the background count (1360 cpm) and the first peak count, the minimum counting time (t) can be obtained to determine a 3σ difference between signal and background.

$$t = \frac{\sigma^2[\text{Background} + (\text{Background} + \text{Signal})]}{\text{Signal}^2}, \quad (2)$$

where t is in minutes, σ is 3, and Background and desired detectable Signal are in counts per minute.

Solving Eq. (2) yields a time of 0.395 min. Therefore, based upon this calculation, a 1-min count should easily determine the amount of carbon-14 produced during the soil pyrolysis to more than a 3σ difference between background counts and 10^4 dpm plus background counts. In order to obtain a reasonable χ-squared interpretation of the count and to provide a contingency against spurious system noise, the data period was increased to 16 one-minute count periods.

D. Experiment sequence

At the start of the first experiment cycle, the heaters and thermoelectric (TE) coolers are activated, and the incubation cell is allowed to temperature stabilize. The SDA drops 0.25 cm^3 of soil into a test cell at the load port position. The PR test cell is then lowered, rotated, and sealed to the incubation head end. At this point, water vapor may be added if desired. This injection of water vapor is effected by opening valve S-7. Then the $^{14}CO_2/^{14}CO$ tracer gas is injected into the test cell head space from the reservoir by alternately opening and closing valves S-5 and S-6. If artificial Martian sunlight is required for the experiment, the lamp is activated at this time and the incubation of the soil is begun.

If the experiment is to be an incubation of a sterilized soil, then once the cell has been sealed under the incubation head end, the cell is raised to a temperature of 85 °C to remove any water vapor with the vent line valve S-12 open. The S-12 is closed and the cell is raised to 180 °C for 3 h to sterilize the soil. The incubation head end is kept at a minimum temperature of 120 °C during this operation. Once the heaters are turned off, the cell cools to the temperature of the local environment and then radioactive incubation gas is added. The remainder of the experiment is performed in exactly the same manner as an active experiment.

In Fig. 14 the incubation sequence is shown in block diagram form. During the time that the soil is incubating at the incubation station, the analysis part of the experiment is preparing for the soil pyrolysis, and both stations are operating in parallel.

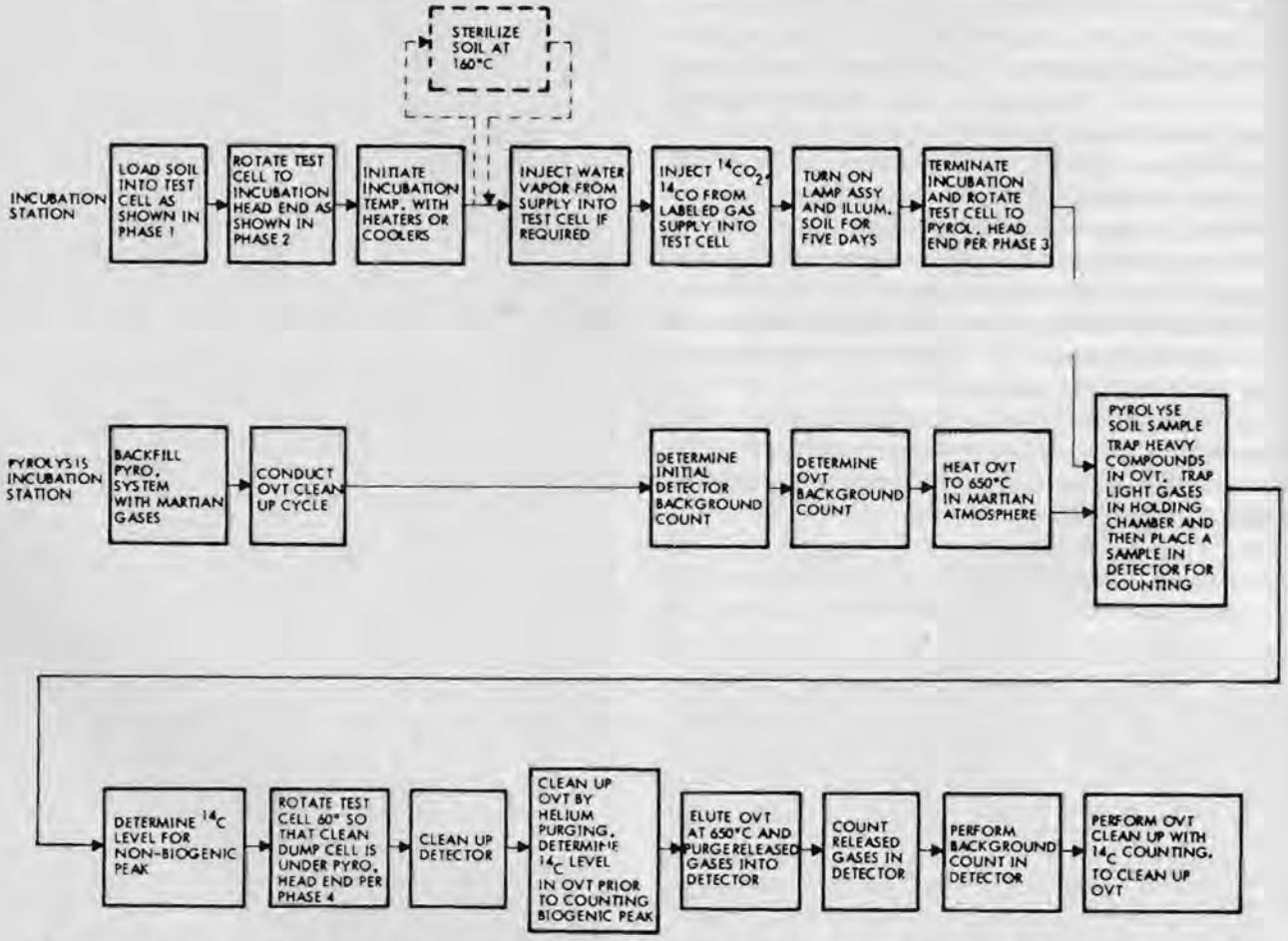

FIG. 14. Pyrolytic release experiment sequence diagramming the major events as blocks of activity throughout one soil analysis cycle.

During the incubation period, the pyrolysis station had been filled with Martian atmosphere to equilibrate the hardware surfaces, especially the OVT, with ^{12}CO and $^{12}CO_2$. At the start of the soil incubation, during the period when the cells are dropped to index a new position, the pyrolysis system is refilled with Martian atmosphere. On the third day of the soil incubation, the OVT is heated to measure its background level of adsorbed ^{14}C gases. This sequence involves heating the OVT to 625 °C (H-3 on for 3 min) in a 1.5-std cm^3/min helium purge which carries any desorbed gas into the detector for counting.

After this background heating, the OVT is vented (S-11 open) for requilibration with Martian atmosphere. At this point the helium purge is discontinued and not restarted in this or the other two experiments until just prior to pyrolysis. This ensures that the system is completely equilibrated with $^{12}CO_2$ and ^{12}CO prior to the exposure for 8 h and then the gases in the detector are allowed to diffuse out of the module via the vent line. However, the detector counting continues until pyrolysis, in order to obtain an accurate value for the general background level of radiation. Only one other operation at the pyrolysis station occurs prior to pyrolysis and that is a further $^{12}CO_2$ and ^{12}CO system equilibration process. Approximately 2 h before pyrolysis, the OVT is heated to 625 °C for the normal 3-min period and then it is allowed to cool to 120 °C, its pyrolysis set point, in the Martian atmosphere. The incubation is terminated after 5 days, and the test cell is vented by opening S-12 and allowing the $^{14}CO_2/^{14}CO$ mixture to diffuse from the cell. After 20 min, the test cell is heated to 120 °C for 30 min to speed diffusion and desorption of ^{14}C gas from the soil. One minute before the cell heater is turned off, the incubation cell is lowered. It is then rotated and sealed to the pyrolysis station. The helium flow is initiated and for 8 min, while the pyrolysis head end and exit line are heating to approximately 200 °C, the helium flows through the cell and OVT and out of the vent line via S-11.

The analysis is started by closing vent valve S-11, and pyrolyzing the soil at 625 °C in the stream of helium. The helium purge transports the volatile products of the pyrolysis to the OVT through a heated (~200 °C) line between the head end and the OVT and then into the detector and holding chamber. The majority of heavy molecular weight compounds condenses in the OVT which is maintained at 120 °C during pyrolysis. With the OVT at 120 °C, approximately 99.99% of the $^{14}CO_2/^{14}CO$ gas released from soil during pyrolysis is carried through the OVT into the detector and holding chamber, which are pressurized to 1070 mbars by the carrier gas during the process. From then on, the PR experiment activity is confined to the analysis procedures at the pyrolysis station (Fig. 14).

The amount of $^{14}CO_2/^{14}CO$ that passes through the OVT needs to be measured since the amount retained by the OVT is a function of the amount to which it was exposed. Since the majority of this nonbiogenic $^{14}CO_2/^{14}CO$ is released from the soil early in the pyrolysis heating, the holding chamber, which fills with gas before the detector, contains a high proportion of the gas. The holding chamber is isolated (close S-9), and the detector is vented to Martian pressure (open S-11, open and close S-8). Opening S-9 then fills the detector with a portion of the holding chamber contents. This gas is then counted as the first peak (nonbiogenic). After the count period, the radioactive gases in the detector and holding chamber are vented. The detector is cleaned by heating for 2 h at 109 °C. During this heating, the OVT and detector are purged with helium to remove residual $^{14}CO_2/^{14}CO$.

Following detector cleanup, there are two helium purges of the OVT and detector to remove adsorbed radioactive gases. The first purge is conducted with the OVT at ambient temperature. The helium from the last 2 min of this purge is trapped in the detector and counted for 6 h. The OVT is heated to 120 °C during the second purge, and again a portion of the purge is counted in the detector for 2 h to measure the level of radioactive gases in the OVT.

After measuring the ^{14}C background of the OVT, an evaluation of the trapped organics is made. This is performed by heating the OVT to 625 °C for 3 min. Any organic compounds volatilized from the OVT during this heating are oxidized to CO_2 by the CuO in the OVT packing. The resultant effluent is carried into the detector by the helium gas stream and counted for at least 12 h. This second (organic) peak is thus composed of assimilated carbon-14 formed during the 5-day incubation period and any residual $^{14}CO_2/^{14}CO$ gases still retained by the OVT.

Once the second peak has been determined, another 12-h, ^{14}C background count is performed. This essentially ends the experimental analysis. However, the elution of the OVT to 625 °C only removes 99% of any organic material condensed out during the pyrolysis. The OVT now needs to be cleaned of this residual material. The OVT is, therefore, eluted twice more for 3 min at 625 °C, and after each elution, the gaseous effluent is counted in the usual manner to determine the effectiveness of the cleaning. Finally, the analysis system is vented to the Martian atmosphere to allow the OVT to equilibrate with CO_2 prior to the next experiment.

The PR experiment was tested on Earth in the same full-instrument test as described for the LR experiment. The sequence used was for one active cycle followed by one control cycle in a manner nearly identical to the operations just described. The results (Table VI) are indicative of typical responses of a moderately active earth soil where the pyrolysis carbon-14 (first peak) is of the order of 10^5 dpm for both active and dry heat sterilized control and the OVT elution (second peak) is a minimum of several fold greater for the active over the control.

The PR experiment presents an interesting problem for a test under simulated Martian conditions. Be-

TABLE VI. Pyrolytic release experiment active and sterilized soil response from a test of a flightlike instrument. The events in each of the two test sequences are those summarized in Fig. 14. The detector counts are net with the background removed.

Test	Soil	Incubation condition	Pyrolysis $^{14}C^*$ (first peak) dpm	OVT Elution $^{14}C^*$ (second peak) dpm
Active	10% preincubated, 90% Aiken	Lamp ON Dry 5 days 14°–22°C	5.6×10^5	855
Control	100% Aiken, sterilized for 3 h at 180°C	Lamp ON Humidified 5 days 14°–23°C	6.6×10^5	179

cause the experiment is performed with no added water or only water vapor added, earth soil microorganisms do not assimilate detectable carbon under these dry (by Earth standards) environmental conditions. Therefore, the Earth test of the instrument under Martian conditions was conducted using a soil specifically compounded to give an active response. The soil sample tested on the active cycle only was prepared by mixing 10% of a preincubated soil with the standard Aiken soil so that a positive response of several hundred dpm was built into the soil before it was tested in the instrument. The preincubated fraction was exposed to $^{14}CO_2/^{14}CO$ under light with sufficient water present to allow earth soil microorganisms to metabolize and assimilate carbon-14 from the atmosphere into their organic material. The test conditions are the same as those described for the LR experiment in Sec. V D.

The PR experiment has successfully operated on the Martian surface according to the sequence summary in Table VII. Nine experiment sequences were conducted which returned interpretable science data. On Lander 1 the PR experiment performed the maximum number of sequences (six) as allowed by the capacity of the test cells and the usable helium. On Lander 2 the three sequences in the primary mission provided useful data but the two in the extended mission did not. An interpretation of the Lander 2 instrument's helium consumption in the extended mission has indicated that one valve (S-11) stuck in the open position and precluded collection by pressurization of the carbon-14 material in the beta detector volume for the sequences after the primary mission.

VII. GAS EXCHANGE EXPERIMENT

A. Experiment concept

The gas exchange experiment (GEx) for the detection of biological activity in soil is based on the measurement of changes in the concentration of gases in the headspace over the soil (in an enclosed cell) caused by metabolism and growth of microorganisms.[10] The experiment, devised by experimenter V. I. Oyama and co-experimenters B. Berdahl and G. Carle, is based on a common characteristic of life on earth in which all organisms produce and/or consume various gases such as H_2, N_2, O_2, CH_4, and CO_2. In the GEx experiment, the metabolism and growth of the microorganisms are stimulated either by humidifying the soil or contacting the soil with an aqueous solution containing a variety of nutrients and growth factors. The changes in gas composition are measured by periodically analyzing the headspace composition by gas chromatography. The patterns of gas composition changes with time produced by organisms in terrestrial soils are markedly different from changes caused by nonbiological phenomena.

Preliminary results from Mars operation have been presented elsewhere.[16,17]

TABLE VII. Pyrolytic release experiment summary of Mars surface operations. Each experiment sequence is described by the Viking mission time for start (begin incubation) and final data collection period initiation (collect biological peak) and the experiment identifying characteristics. Sols are number of Mars days elapsed since landing. Sol 0 is July 20, 1976 for Lander 1 and September 3, 1976 for Lander 2. The primary mission is that period over which the instrument was designed to operate. The last two sequences on Lander 2 were performed properly but no useful science data were obtained due to the presumed leak in a valve precluding collection and quantitation of the carbon-14 material.

Experiment description	Receive soil, sol	Sterilize or heat soil, sol (temp.)	Add water vapor	Begin 5 sol incubation, sol	Collect biological peak, sol
Lander 1					
Surface sample—active, light	8		No	8	17
Residual soil—control, light	24	27 (180°C)	No	27	34
Surface sample—active, light	36		No	36	43
Surface sample—active, light	91		No	91	98
End of primary mission					
Residual soil—water vapor and heat	160	160 (85°C)	Yes	160	167
Residual soil—active, light	230		Yes	230	237
Lander 2					
Surface sample—active, dark	8		No	8	18
Surface sample—active, light	28		Yes	28	37
Subrock sample—active, dark	51		No	51	59
End of primary mission					
Surface sample—active, light	145		No	145	154
Residual soil—heated, light	177	177 (85°C)	No	177	186

B. Experiment implementation

The soil sample is delivered to the test cell and sealed gastight. Incubation gas and nutrient solution are added to the test cell and the temperature controlled above freezing but below 27 °C. Gas analyses are periodically made of the cell headspace. At selected intervals the nutrient and incubation gas are replaced with fresh solution and gas. The soil can be thoroughly dried if a second soil is to be added to the single test cell. When desired the soil and cell can be heated to sterilize the soil for a control experiment.

The basic design of the GEx experiment is shown in Fig. 15. The major components of the GEx module are described below.

The single test cell of 8.7-cm^3 volume and dump cell both mounted at opposing positions on a carousel and Geneva wheel rotates to the soil load port and to the head end when lowered by a vertical actuator assembly.

The head end assembly provides the cell seal, inlets for gas and nutrient, and valve S-19A to prevent condensation of water in the line between the head end and the gas chromatographic analysis assembly.

The reservoir assembly contains the nutrient ampoule. This assembly is also equipped with two pistons that are actuated with high pressure helium to puncture the ends of the ampoule.

A gas chromatographic analysis assembly (GCAA) is used to analyze the cell headspace and is composed of a gas sample valve, a pair of matched 7.6-m by 0.1-cm i.d. columns packed with 100–120 mesh Porapak Q, and a thermistor thermal conductivity detector.

A gas reservoir contains a He/Kr/CO_2 mixture used as the incubation gas. A gas reservoir (physically located on the labeled release experiment module) provides a gas mixture (He/O_2/CO_2) used to pretreat the columns after they have been exposed to space vacuum during the interplanetary voyage.

Heaters are used to sterilize or dry the soil in the cell, if necessary, sterilize portions of the nutrient system, control the temperature of the cell, nutrient system, and lines exposed to water, and provide constant GCAA

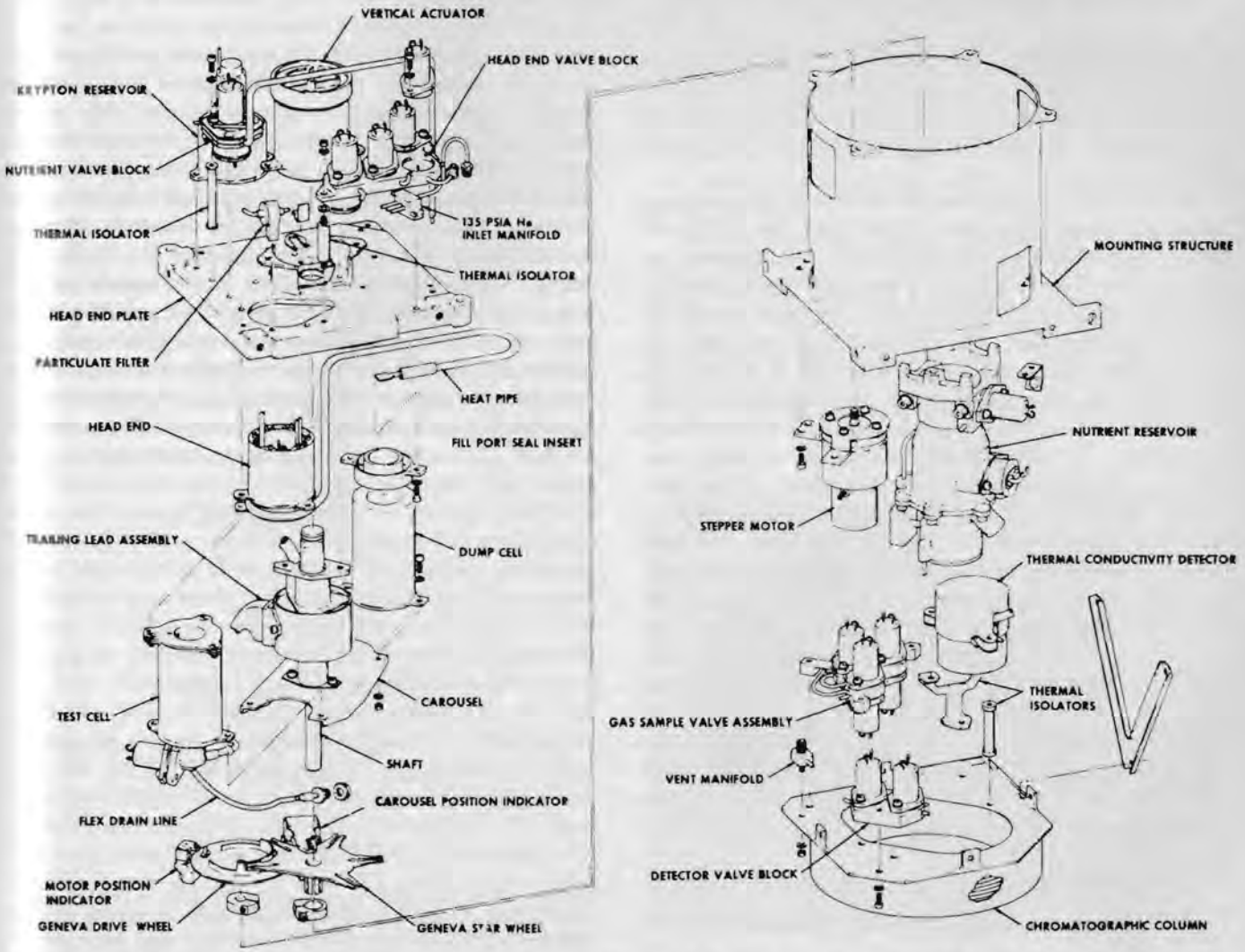

FIG. 15. Exploded view of the gas exchange experiment module assembly. For clarity the gas and liquid lines which purge the test cell, rejuvenate the chromatograph columns, provide chromatograph helium flow, and inject nutrient are not shown.

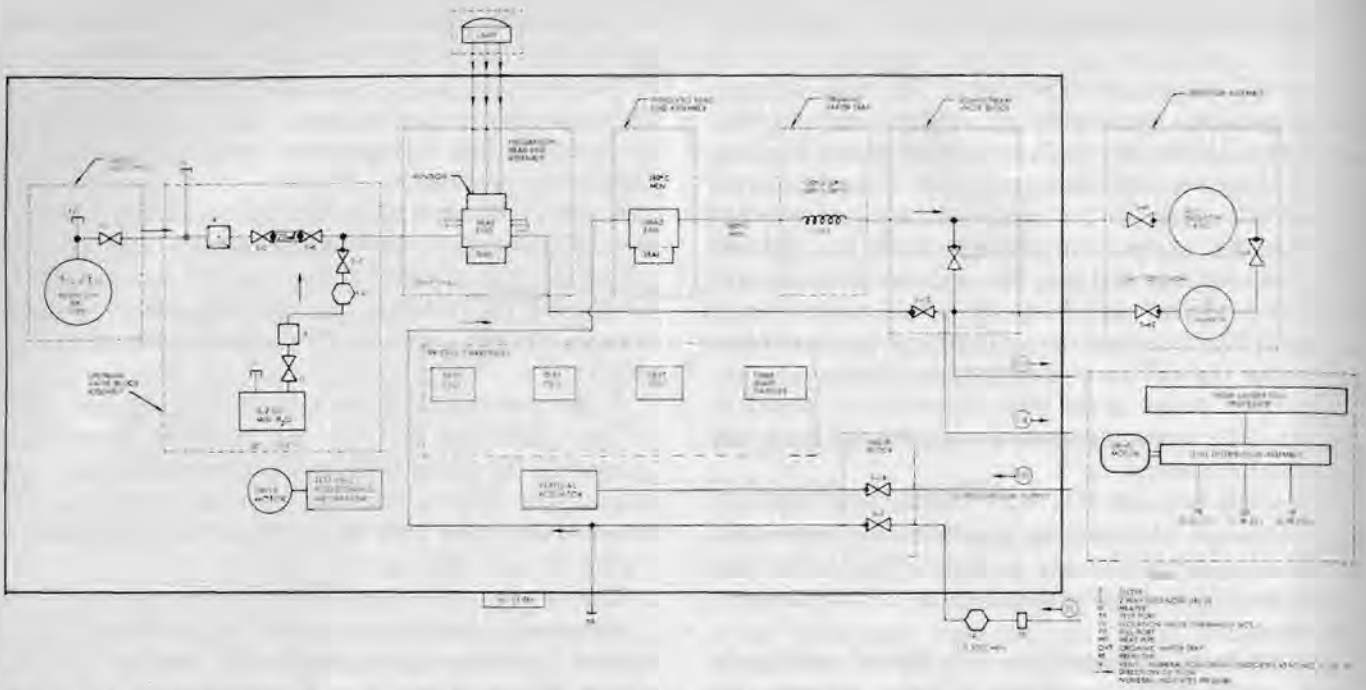

FIG. 16. Gas exchange experiment module flow diagram. The module contains one test cell which receives soil and seals at the head end. The components for conducting the soil incubation are shown in the lower portion of the diagram, and the lines, valves, columns, and detector of the gas chromatograph are in the upper portion.

column temperature (±0.5 °C) and constant detector temperature (±0.1 °C) during analyses. Cooling of the test cell is provided by thermoelectric coolers attached to a heat pipe to prevent overheating of the soil during incubation.

Other important components necessary to the experiment operation which are shared with the other two biology experiments include the soil distribution assembly, the high- and low-pressure helium supplies and a 77 000-std-cm³ He reservoir, the vent manifolds and a liquid sump and charcoal trap assembly to minimize the effect of substances vented by the biology instrument on other experiments on the lander, and the electronic subsystem for experiment control and for data processing. The relationships among the various components and the functional flow are shown in Fig. 16.

The GEx test cell and head end were designed to include capacity for two 1-cm³ soil samples; ability to humidify the cell without nutrient contacting the soil; capability of wetting the soil from the bottom to the water holding capacity of the soil without the soil sample being completely submerged; maintenance of a liquid path between the nutrient in the soil and the remainder of the nutrient in the cell; ability to drain most of the nutrient from the cell without opening the cell; a head-space volume in the range of 4–10 cm³; and daily leak rates less than the detectable limits of the chromatographic analysis system ($<0.7 \times 10^{-3}$ std cm³ per day for CO_2).

Temperature requirements include maintenance of 15 $^{+12}_{-10}$ °C during incubation and 140 °C minimum for 3 h for the control heating from the soil chamber to the cell drain valve and nutrient injection valve block.

A cross section of the GEx test cell and head end is shown in Fig. 17. The cell consists of two stainless steel cups with a total volume of 8.7 cm³. The inner cup receives the soil sample and has a bottom consisting of a 10-μm (nominal) pore size sintered stainless steel frit. The inner cup also has six small sintered stainless steel frits above the soil level to allow gases to equilibrate between the inner cup and the outer cell body. The nutrient is conducted to the bottom of the outer cell from the head end by a small stainless steel tube so that the nutrient does not contact the inner cup bottom frit (and hence the soil) until somewhat more than 1 cm³ of nutrient has been added. The inner cup is positioned such that when the nominal full amount of nutrient (2.5 cm³) has been added, the soil is not

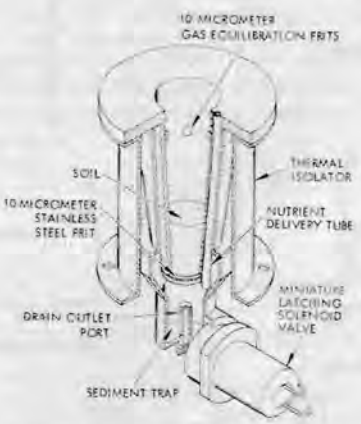

FIG. 17. Cross section of the gas exchange experiment test cell showing the location of the soil in the suspended, inner cup, and the nutrient volume which is filled from beneath the soil cup. The bottom of the cup is fritted stainless steel to allow the nutrient to reach the soil. Gas samples are taken by the gas chromatograph from the head-space above the soil.

TABLE VIII. Gas chromatograph analysis requirements.

Gases separated	H_2, N_2, O_2, CH_4, Kr, CO_2 (CO and Ar are part of the O_2 peak)
Resolution	95% between peaks of 70 nM of N_2 and 7 nM of O_2
Sample size	0.1 cm^3
Sensitivity	Minimum detectable quantities in nM H_2 : 10 CH_4 : 0.5 N_2 : 0.25 Kr : 0.4 O_2 : 0.3 CO_2 : 1.0
Precision	5% between 40 and 400 times the minimum detectable quantity
Carrier gas purity	>99.999%
Data sampling rate	Constant throughout chromatogram

completely submerged, and is in contact with the bulk of the nutrient in the cell. The large excess of nutrient in the outer cell body acts as a reservoir to dilute metabolic products generated by any soil organisms which might otherwise interfere with continued growth and metabolism. When only humidification of the cell is desired, approximately 0.5 cm^3 of nutrient is added by a 1-min injection at a nominal flowrate of 0.5 cm^3/min.

The connections to the test cell are the cell drain line (0.32 cm o.d. Teflon tube), drain valve leads, and cell heater and sensor electrical leads. These lines are connected from the cell to the rest of the module via a trailing lead assembly. The cell is rotated 180° in one direction to reach the load port and then 180° in the opposite direction to return to the incubation position. The drain line and valve are required so that the cell can be drained when desired prior to adding fresh nutrient or prior to drying the cell without opening the cell. The drain line leads to a sump and charcoal trap assembly which allows evaporation of water but retains organic compounds which might otherwise give false responses in the molecular analysis (gas chromatograph–mass spectrometer) experiments.[23]

The head end assembly contains all of the lines which were not required to be connected to the cell itself. The lines leading into the cell via the head end are the nutrient line coming from valve S-22, the line providing incubation gas (from valves S-24 and S-25) and low pressure (1.2 bars) helium (from valve S-23), and the line leading to the gas chromatographic analysis assembly (GCAA). This line is closed at the head end with valve S-19A to prevent water from condensing in the line during the diurnal temperature variations. The placement of the GCAA with respect to the head end was determined by volume utilization requirements and the modularized design of the overall instrument. The head end also contains the heat pipe termination from the thermoelectric cooler, the cell seal, and a Kapton film heater which is used for the control heating. The nutrient valve block is heated to sterilization temperatures with a separate heater. Thermal control of the cell during incubation is achieved by heating with the module (can) heater mounted on the module structure or by cooling with the thermoelectric cooler and heat pipe as required. The cell temperature requirement during incubation is greater than 5 °C and less than 27 °C. For the control (sterilization heating), the head end and cell body are simultaneously heated to insure that no cold spots are present. The control heating requirement is 140 °C minimum for the cell and head end. The nutrient line is heated during the control sterilization to 120 °C minimum near the valve block. The valve block and surrounding area are heated to an average 130 °C prior to all but the first nutrient injections.

1. Chromatographic analysis system

The lower part of the GEx module contains the gas chromatographic analysis assembly (GCAA) and the nutrient reservoir. The GCAA is a specialized gas chromatograph for the analysis of gases of biological interest. The basic requirements of the analysis system are listed in Table VIII.

The GCAA is basically a conversion to flight hardware of the chromatographic system used in the laboratory.[22] The GCAA (Fig. 18) is 9 cm square by 6 cm high and consists of a gas sampling system, a pair of matched porous polymer bead chromatographic columns, and a thermistor thermal conductivity detector.[26] The carrier gas (He) is supplied by the He tank and regulators in the common services module (discussed under common support elements). The detector data processing is carried out in the electronic subsystem (ESS).

The gas sampling system contains the largest deviation from typical laboratory operation. The usual laboratory gas sampling system is a six- or eight-port rotary gas sample valve. Pneumatic and electrical actuators are available for these valves. However, these devices had the drawbacks of being bulky and heavy. The flight system used a manifold of the mini-

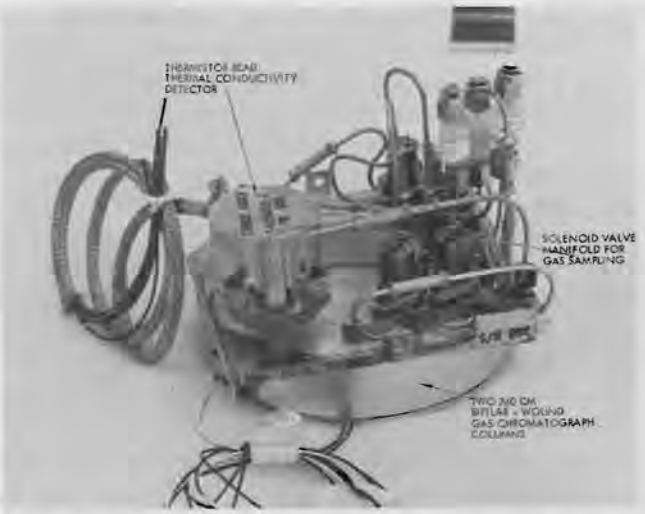

FIG. 18. Gas exchange experiment gas chromatograph analysis assembly. The assembly consists of a gas sampling system, two gas chromatograph columns, and a thermal conductivity detector.

ature latching solenoid valves (MLSVs) which are discussed in detail under common support elements. This approach provided substantial weight and volume savings over alternate concepts. Manifolds of grouped or ganged valves have been used in the past for gas chromatographic sampling, but the performance of these systems was usually poor because of the volume effects. However, the small size of the MLSVs overcomes these deficiencies, and testing demonstrated that a manifold of five valves (S-17 through S-21) could acquire a representative sample of gas from the test cell with a minimum of sample consumption and only a slight loss of resolution when compared to a conventional laboratory rotary type "microvolume" gas sampling valve. Typical N_2–O_2 resolution with a rotary laboratory valve is 99% compared to 98% for the flight system.

The chromatographic columns consist of a matched (pressure drop) pair of 760-cm-long, 0.11-cm-i.d., 0.013-cm wall thickness stainless-steel tubes packed with 100–120 mesh Porapak Q, batch 1182. The performance of these columns is similar to that of the column described in Ref. 22. The use of matched columns was a conservative approach to providing a reference flow to the detector to minimize baseline drift at a slight cost in extra weight. The use of 0.11-cm-i.d. columns provides excellent separation of N_2 and O_2 at 24 °C with good sensitivity. The pressure drop is large for these columns (typically 6.7 bars at 13.5 std cm³/min flow) but this does not interfere with sampling or column performance. The flow-rate used was 13.5 std cm³/min which is near the optimum flow-rate for N_2–O_2 resolution with this system.

The column pressure drop was matched to the output of the He supply high-pressure regulator (9.07 ± 0.34 bars) by the use of 0.0076-cm-i.d. capillary tubing upstream of the columns (and control valves) for flow restrictors. The column temperature of 24 °C was selected as the best tradeoff between resolution and ability to control the column temperature by heating only. The columns are bifilar wound in a 8.9-cm-o.d. coil 1 cm thick. The column heater is a film type applied to the inside of the mandrel, and is proportionally controlled during chromatographic operation. External insulation of the column assembly (and detector) is not required because the amount of convection heat loss is small under Martian atmospheric conditions.

The pneumatic connectors between the columns and the rest of the system are the standard solder joints described under common support elements. The column packing is held in place with small plugs containing a large number of "straight-through" holes approximately 5×10^{-3} cm in diameter. Some difficulty was encountered during the hardware development phase with migration of fragments of the packing material. To minimize this, Pyrex wool was added as a fiber filter between the column plug and the solder joint during instrument assembly. The Pyrex wool was in turn held in place by another plug entrapped in the solder joint.

The detector used is a low dead volume thermistor type thermal conductivity detector proportionally heated to 32 °C during GCAA operation with a heater mounted on the gold plated copper block. The thermistors are operated in a bridge circuit that maintains their resistance and, hence, temperature constant at 800 Ω which corresponds to approximately 100 °C. The signal output of the bridge is the variation in the power required to maintain the active thermistor at 800 Ω versus the reference side. The advantages of the constant temperature circuit are greater stability. Furthermore, the detector can be operated for testing purposes in any environment including vacuum and earth ambient air without any possibility of thermal stress on the beads.

The control of the thermistor is accomplished by the GEx low level electronics (LLE) which is located in the electronic subsystem (ESS). The GEx LLE also provides for periodic reset of the baseline, and conditions the signal output from the bridge so that the signal will match the input requirements of the analog to digital converter (A/D). The A/D is designed for positive only signals with a range of 5 mV (size of the smallest bit of the A/D) to 5 V, while the voltage range of interest from the detector bridge circuit is 0.005 to 50 mV. A range switching amplifier with gains of either 1000 or 100 is used to match the bridge output to the A/D input. In order to preclude the possibility of negative signals, the output is offset from zero to 0.5 V at gain of 1000 and 0.05 V at gain of 100. The range of switching allows a total dynamic range of 10 000 which is sufficient to monitor all of the gases of interest within the likely range of gas composition changes.

2. *Nutrient system*

The GEx nutrient is a complex aqueous solution[10] whose composition is shown in Table IX. It is intended to provide essentially all factors which stimulate and sustain growth of various types of microorganisms without being inhibitory to any special types. The nutrient is contained in a Pyrex glass ampoule similar to that used in the LR experiment except that the GEx ampoule is somewhat larger. The amount of nutrient in the ampoule is approximately 15 cm³ (13.5 cm³ minimum delivered volume) as compared to the maximum of 12 cm³ required for four experiment cycles.

The nutrient was prepared at NASA/Ames Research Center under the direction of the GEx experimenter, V. I. Oyama, and provided to TRW for loading into the flight ampoules. All equipment used in loading which could contaminate the nutrient with microrganisms was autoclaved prior to use. The ampoule loading operations were conducted in a glove jar under an atmosphere of flowing helium. The nutrient was deaerated by bubbling 80% neon, 20% helium through the solution prior to placing in the Pyrex glass ampoule. The gas above the nutrient in the filled ampoule was analyzed to contain less than 1000 ppm air. The filled ampoule containing Ne/He gas above the nutrient was

TABLE IX. Composition of the gas exchange experiment nutrient. The solution after encapsulation in Pyrex glass has been sterilized three times: 45 min at 125°C, 54 h at 120°C and 21 h at 112°C.

Amino acids (A-4)	Formal conc: m*M*
DL-Alanine	2.0
DL-Arginine·HCl	1.0
DL-Aspartic acid	1.5
DL-Citrulline	0.5
DL-Cystine	0.3
DL-Glutamic acid-HCl	2.0
Glycine	1.3
DL-Histidine	1.3
DL-Isoleucine	1.0
DL-Leucine	0.8
DL-Lysine-HCl	2.0
DL-Methionine	0.7
DL-Phenylalanine	1.2
DL-Proline	1.7
DL-Serine	1.0
DL-Threonine	1.0
DL-Tryptophan	0.3
DL-Tyrosine	1.0
DL-Valine	1.7

C, H, O (C-4)	Formal conc: m*M*
Na acetate·$3H_2O$	26
Na citrate·$2H_2O$	0.7
Na formate	10
Glycerol	39
DL-Na lactate	22

Additional factors (E-4)	Formal conc: *M*
Putrescine	5×10^{-5}
Tween 80	0.1 mg/l
Adenine	2×10^{-6}
Guanine·HCl	2×10^{-6}
Uracil	2×10^{-6}
Xanthine	2×10^{-6}

Vitamins (B-4)	Formal conc: *M*
Ascorbic acid	3×10^{-4}
Biotin	2×10^{-9}
Choline Cl	4×10^{-5}
Cobalamin	7×10^{-10}
i-inositol	6×10^{-5}
Nicotinic acid	4×10^{-6}
Nicotinamide	4×10^{-6}
Ca pantothenate	1×10^{-6}
Pyridoxal HCl	5×10^{-7}
Pyridoxine HCl	2.5×10^{-6}
Pyridoxamine 2 HCl·H_2O	2×10^{-6}
Riboflavin	3×10^{-7}
Thiamine·HCl	1.5×10^{-6}
β-alanine	6×10^{-6}
DPN	1×10^{-5}
Folacin (folic acid)	3×10^{-8}
PABA	8×10^{-9}

Salts (D-4)	Formal conc: m*M*
H_3BO_3	1×10^{-10}
$CaCl_2 \cdot 2H_2O$	3×10^{-3}
$CuSO_4 \cdot 5H_2O$	8×10^{-6}
$MgSO_4 \cdot 7H_2O$	3×10^{-4}
$MnCl_2 \cdot 4H_2O$	2×10^{-7}
$(NH_4)_6 Mo_7O_{24} \cdot 4H_2O$	2×10^{-8}
KNO_3	1×10^{-2}
KH_2PO_4	8×10^{-3}
$ZnSO_4 \cdot 7H_2O$	7×10^{-6}
NH_4VO_3	2×10^{-7}
$Co(NO_3)_2 \cdot 6H_2O$	2×10^{-7}
$FeSO_4 \cdot 7H_2O$	5×10^{-7}
$Na_2EDTA \cdot 2H_2O$	3×10^{-3}

sealed by standard glass blowing technique. The external surfaces of the ampoule were cleared to remove adsorbed helium prior to checking for helium leakage with a mass spectrometer leak detector as an indication of proper sealing. The ampoule was finally sterilized at (125° ± 2°)C for (45 ± 5) min and stored prior to installation into the instrument.

Neon was selected for addition to the ampoule to act as a nutrient delivery diagnostic. Nutrient delivered to the test cell outgases dissolved neon which is then detected in the chromatographic analyses. Helium is present for the external leak check of the sealed ampoule.

The nutrient ampoules were inserted aseptically into their stainless steel housing at TRW prior to sterilization of the instruments and shipment to Kennedy Space Center for installation into their respective Landers.

Control of the amount of nutrient delivered to the test cell is different for GEx than for LR. In the case of the GEx experiment, because the delivered nutrient quantity was larger, timed flow through a restrictor is used rather than a trapped volume. This restrictor (7.6×10^{-3} cm i.d., 30 cm long) provides approximately 0.5 cm^3/min flow for a 0.1-bar pressure differential. Since the minimum sequencing time for the nutrient valve is 1 min, the quantity of nutrient delivered can be controlled in 0.5-cm^3 increments. The narrow restrictor is protected from particles with 10-μm nominal pore size "dutch weave" filters.

3. Gas supplies

In addition to the He supply shared by all three experiments, GEx has two special gas supplies used within only this experiment. There is a He/Kr/CO_2 gas mixture for the incubation gas and a He/O_2/CO_2 gas mixture for pretreatment of the chromatographic columns after their long exposure to space vacuum. These two mixtures are contained in reservoirs of approximately 10 cm^3 volume at pressures in the range of 8 to 10 bars.

The incubation gas composition is 5.51% Kr, 2.84% CO_2, with the balance He. Kr is used as an internal standard both for retention time purposes and as reference against which gas changes can be monitored. The CO_2 is present to simulate the Martian atmosphere, and He is present to provide adequate pressure to obtain a representative sample for chromatographic analysis. The incubation gas is introduced into the cell by opening valve S-25 (with S-24 closed) for 1 min, closing S-25, and then opening S-24. The pressure in the reservoir is matched to the volume between S-24 and S-25 so that under nominal conditions with 1 cm^3 of soil present (assuming 50% void volume) and 2.5 cm^3 of nutrient added, the Kr partial pressure would be 10 millibars, CO_2, 5 millibars and the total cell pressure would be 200 millibars.

The column pretreatment (rejuvenation) gas reservoir was added late in the design of the instrument and is physically located on the LR module. In the initial design of the GCAA, it had been intended to seal the columns during interplanetary cruise with the GCAA valves to prevent exposure to space vacuum. Later in the development program it was determined that leaving these valves closed for about 1 year was unwise because of the possibility of valve stiction. Laboratory testing indicated that exposure of the columns to space vacuum resulted in certain reversible adsorption phenomena which caused partial loss of the sample in the initial chromatographs after vacuum exposure. Testing also indicated that the problem could be corrected by exposing the columns to a CO_2/O_2 gas mixture in He prior to the use of the columns for analysis. Prelaunch testing with accelerated exposure at elevated temperatures and long-term vacuum exposure tests verified the efficiency of this rejuvenation process.

C. GEx experiment operation

Because the biology sequencer is addressable, a high degree of flexibility in experiment operation through commands from Earth is possible. However, the ex-

periment is operated as much as possible according to the preprogrammed sequence steps in order to minimize the number of commands required.

On sol 3 after landing, the rejuvenation procedure is conducted where the 100 std cm^3 of 10% O_2 and 10% CO_2 in helium is allowed to flow through both Porapak Q columns and out to vent through valves S-17 and S-18 (Fig. 16) in a one-time operation. A sample of the rejuvenation gas is trapped in the sample loop during the He purge removal procedure which flows forward through the reference column and backward through the sample column with S-15 closed. This sample is analyzed by the gas chromatograph as a diagnostic to demonstrate the O_2/CO_2/He rejuvenation of the columns actually occurred.

The details of a chromatographic analysis of the test cell gas are as follows. First the column and detectors are heated to their operating temperatures prior to initiating a carrier gas flow. Time of day constraints on the analysis insure that it is conducted when the instrument environment is cool enough to allow proper control of the temperatures. Before sampling the cell head space, the gas in the sample loop between S-18 and S-19 and the gas between S-19 and S-19A are removed by pressurizing the volumes with 9.2-bar psi helium from S-21 and venting through S-18. This is done twice and the second time S-18 remains open for 3 min to assure that proper venting of the sample loop to Mars ambient pressure occurs. Flow through the columns is then started by opening valves S-16, S-20, and S-15, which is the normal carrier flow path except during sample injection. With S-18 closed, sampling of the cell head space is carried out by opening S-19. The reason the $He/Kr/CO_2$ incubation gas contains helium is that the helium acts as a pressurant so that the cell pressure will always be significantly higher than Martian ambient pressure. After S-19 and S-19A have been open 1 min, they are closed and S-18 is opened for 1 min. The loop fill and venting is repeated and a final third loop filling is made. This traps a representative sample of the cell head space in the 0.11-cm^3 loop volume with a total consumption of approximately 0.5 cm^3 of head space gas (including the gas in the line between S-19 and S-19A which is vented prior to the next analysis). After the sampling procedure is complete, valve S-21 is opened to pressurize the loop, and 1 min later valve S-20 is closed simultaneously with the opening of valve S-17 to sweep the sample into the active column. Then 8.2 s (using a special timing circuit) later S-17 and S-21 are closed and S-20 reopened. The sample is swept through the column where it is separated into the individual components which are detected by the thermal conductivity detector. The loop is pressurized with 9.2-bar He prior to opening valve S-17 to minimize backflow from the high-pressure column into S-17 which would occur if S-17 was opened with high pressure in the column and low pressure in the loop.

The applied detector signal from the GEx low-level electronics is sampled once per second during the 16-min chromatogram producing 960 data points which are transferred to the Lander memory for transmission to Earth. The chromatogram is then reconstructed by computer from the received data points.

It is known that a signal can be reconstructed with zero error from samples taken at a continuous rate equal to 2 Ω, provided that no frequency components exist at a frequency higher than Ω (the Nyquist frequency). While this requirement is not completely satisfied by the biology instrument chromatographic data, the data do meet it closely enough to allow accurate reconstruction of the sampled data. The peak shapes produced by the GEx experiment are close approximations to a Gaussian profile and Gaussian peaks have suitable characteristics for reconstruction because of rapid convergence (due to the exponential factor) in both the time and frequency domains.

In the case of an ideal Gaussian distribution, a sampling interval equal to the standard deviation of the Gaussian in the time domain is adequate for accurate peak reconstruction. In the case of the GEx experiment, the sampling interval is 1 s, which means that peaks with full-width at half-maximum greater than 2.36 s can be reconstructed with better than 1% accuracy. The GEx peak widths vary from approximately 3 s (H_2 and N_2) to 15 s (CO_2), which easily satisfies the requirement.

There are a number of other factors involved in the flight hardware system. Baseline drift does not interfere with the reconstruction process of experimental chromatograms since any sampling rate adequate to characterize the peaks is adequate for the baseline. Baseline noise is not well characterized because the noise bandwidth is large in comparison with the Nyquist frequency. However, reconstruction of the baseline noise is not at all important in the characterization of the chromatographic data. Peak tailing effects do not interfere since they tend to increase the effective peak time constant. Column overloading can cause distorted peaks with a rapidly rising leading edge which is not well reconstructed. This error is relatively small and does not occur in the normal range of peak heights obtained with the GEx experiment.

Figure 19 shows a chromatogram from above a Martian soil reconstructed from one sample per second data. Comparison of more than 300 reconstructed chromatograms obtained during development tests with the conventional analog output has uniformly showed agreement within experimental error of usually less than 1% between the peak heights and the peak areas of the two methods.

After reconstruction of the chromatograms from the digital data, the components in the sample are identified by retention time. The peak heights and areas are used in conjunction with calibration data obtained during instrument fabrication to determine the amount of each component present. Extensive calibration was carried out at the GCAA level over a 1000 : 1 range in component quantity starting at a level corresponding

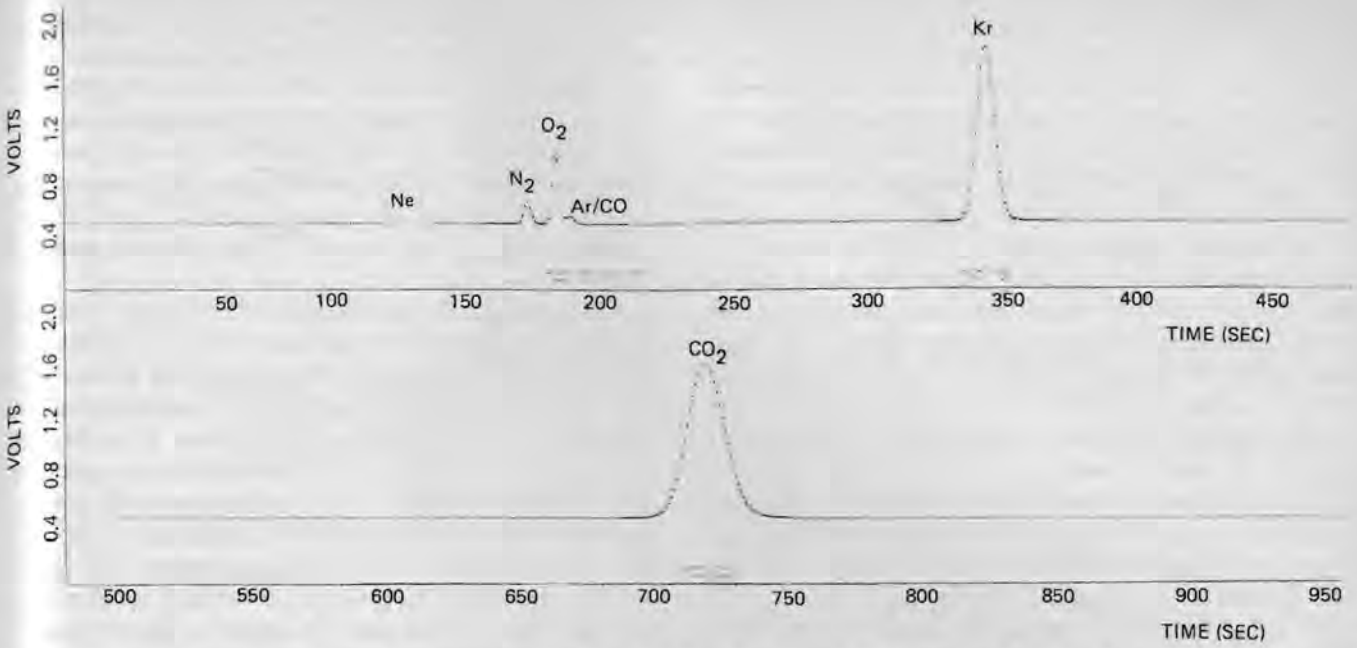

FIG. 19. Chromatogram reconstructed from once per second data. The data shown here is the first gas analysis taken from above the Martian soil after exposure to water vapor (Lander-1, sol 9; July 29, 1976).

to the minimum detectable quantity. In practice, the GCAAs were more sensitive than originally specified by factors of 2 to 3 for all of the required components.

In addition to the required H_2, N_2, O_2, CH_4, Kr, and CO_2, the system can measure other gases such as Ne, Ar, CO, NO, and N_2O. The Ne retention time is 7 s less than H_2 but the peaks are well resolved. The NO retention time is somewhat longer than CO, and N_2O occurs near the end of the 16-min chromatogram. The chromatogram can be extended past 16 min by command to insure the detection of any possible N_2O.

The peak height (and area) is proportional to the quantity of the component injected. Typical sensitivities in terms of nanomoles per sample volume (0.11 cm^3) are H_2: 3, N_2: 0.08, O_2: 0.1, CH_4: 0.2, Kr: 0.15, CO_2: 0.35. These sensitivities correspond to a peak height of 10 mV (including the electronic gain factor of 1000) which is twice the size of the least bit of the A/D converter. The maximum voltage effective peak height that can be measured (with range switching) is 50 V so that the operating dynamic range is 5000 to 1. The response in terms of log peak height or area versus log nanomoles is linear up to approximately 500 n*M* with a slope close to unity. Some curvature occurs above 500 n*M* but the response is still easily interpretable. Parametric variation tests were also obtained for some GCAAs at off-nominal pressures and temperatures to provide data correction capability.

A few chromatograms were also obtained on the complete biology instruments during acceptance testing to provide correction factors to differences in gain factors and set points between the GCAA test equipment and the actual flight systems. These corrections were small for Viking 2, but in the case of the instrument in Viking 1, a pressure dependence was found at the instrument level that did not exist during the GCAA component tests. This pressure dependence is such that the response depends not only on the component partial pressure in the test cell but also on the total cell pressure. The magnitude of the effect was insignificant at test cell pressures in the range of 1 bar, but at pressures in the 100-millibar range (which is the lower end of the nominal test cell pressure range) the response was as much as 20% lower than predicted. This effect is thought to be caused by excessive restriction in the sample loop outlet restrictor assembly which prevents complete venting of He from the sample loop and line from the cell to the GCAA during the loop and line pressurization and venting which normally precedes sample acquisition (conducted to prevent any carryover of sample trapped in the line from one analysis to the next). This effect has been corrected for actual mission operations by the use of data obtained during instrument diagnostic testing and sequence changes to maintain the cell at somewhat higher than usual pressures (usually above 600 mbars). Since the incubation gas contains Kr as an internal standard, this pressure dependent effect has little impact on measuring changes in gas concentration in the cell since such changes are referenced to the Kr peak. The correction is of importance only when absolute quantities are desired, as in determining the amount of O_2 evolved from the soil after humidification.

Independent of the above effects, the results must also be corrected for the amount of gas removed from the cell by each analysis. The fractional amount removed per sample depends on the actual head space volume in the cell which in turn depends on the amount of soil and nutrient present in the cell. Typical

values are 6.5% removal per analysis for a humidified case and 8.8% per analysis for a nominal case with 2.5 cm^3 of nutrient injected. Again, the internal standard Kr peak is used to provide the correction.

While the instrument was not designed with the intent to conduct Martian atmospheric analyses as one of the design criteria, there are in fact several ways by which an atmospheric sample can be acquired and analyzed. One simple method is to open valve S-18 for a period long enough (several hours are used in practice) to attain equilibrium between the loop volume and the atmosphere via diffusion. Valve S-18 is then closed, the GCAA warmed and column flow established and the sample injected. The system is sufficiently sensitive that N_2 and O_2 can be detected down to approximately 0.25% for N_2 and 0.3% for O_2 despite the low Martian atmospheric pressure and the small volume of the sample loop. A redesigned system based on the GEx GCAA has been developed specifically for atmospheric analyses on the Pioneer Venus large probe scheduled for launch in 1978.

D. GEx experiment sequence

For the primary mode of test cell analyses, the spacing of analyses is such that they are usually carried out at intervals of one day immediately after nutrient injection to monitor any rapid initial changes and then the spacing is increased with increasing incubation time since any gas changes occurring later in the incubation usually have a slower rate. This spacing provides adequate monitoring for gas changes while minimizing the number of analyses required. A total of 52 gas analyses was run on Lander 1 and 57 on Lander 2 (Table X).

A block diagram presentation of the major elements of the GEx sequence is shown in Fig. 20. In the first incubation cycle, the soil is humidified for a time with only 0.5 cm^3 of nutrient added. The test cell pressure is about 150 millibars at this point. Later in the first incubation an additional 2 cm^3 of nutrient is added to start a typical "active" cycle incubation with the nutrient in contact with the soil and the cell pressure rises to about 200 millibars. On the second and all subsequent nutrient injections, the nutrient valve block and line from the valve to the head end are heated to approximately 145 °C for 3 h to prevent any Martian microorganisms, if present, from migrating through the valve and possibly contaminating the nutrient in the reservoir.

After a period of incubation (whose duration is controlled from Earth), the cell is drained by pressurizing the cell to 1.2 bars with the low-pressure He supply

TABLE X. GEx experiment summary of Mars surface operations. Each experiment sequence is described by the Viking mission time for start and stop (drain cell) and the cycle identifying characteristics. Sols are the number of Mars days elapsed since landing. Sol 0 is July 20, 1976 for Lander 1 and September 3, 1976 for Lander 2. The primary mission is that period over which the instrument was designed to operate. The deep soil chemistry cycle sequence was performed properly but no useful science data were obtained due to the apparent inability of the test cell to retain its pressure.

Experiment description	Soil received, sol	Heat soil to 145°C, sol	Begin experiment cycle, sol	Drain cell, sol	No. of gas analyses
Lander 1					
Extended active incubation	8				
Humid mode			9		5
Wet mode #1				29	6
Wet mode #2			29	68	14
Wet mode #3			68	103	8
Wet mode #4			103	216	12
End of primary mission					
Oxygen release test	230	231			
Dry mode			232		1
Humid mode			234	238	1
Deep acquisition soil chemistry	250				
Dry mode			250		1
Humid mode			252	264	3
Heated soil mode		270	271		1
Lander 2					
Surface soil active	8				
Dry mode			9		3
Humid mode			10		5
Wet mode #1			17	36	8
Wet mode #2			36	49	5
Subrock soil active	51				
Dry mode			52		3
Wet mode #1			55	133	14
End of primary mission					
Wet mode #2			133	149	4
Wet mode #3			149	172	6
Oxygen release test	177	178			
Dry mode			178		1
Humid mode			180	185	3
Heated soil gas release		255, 226, 229		227	4

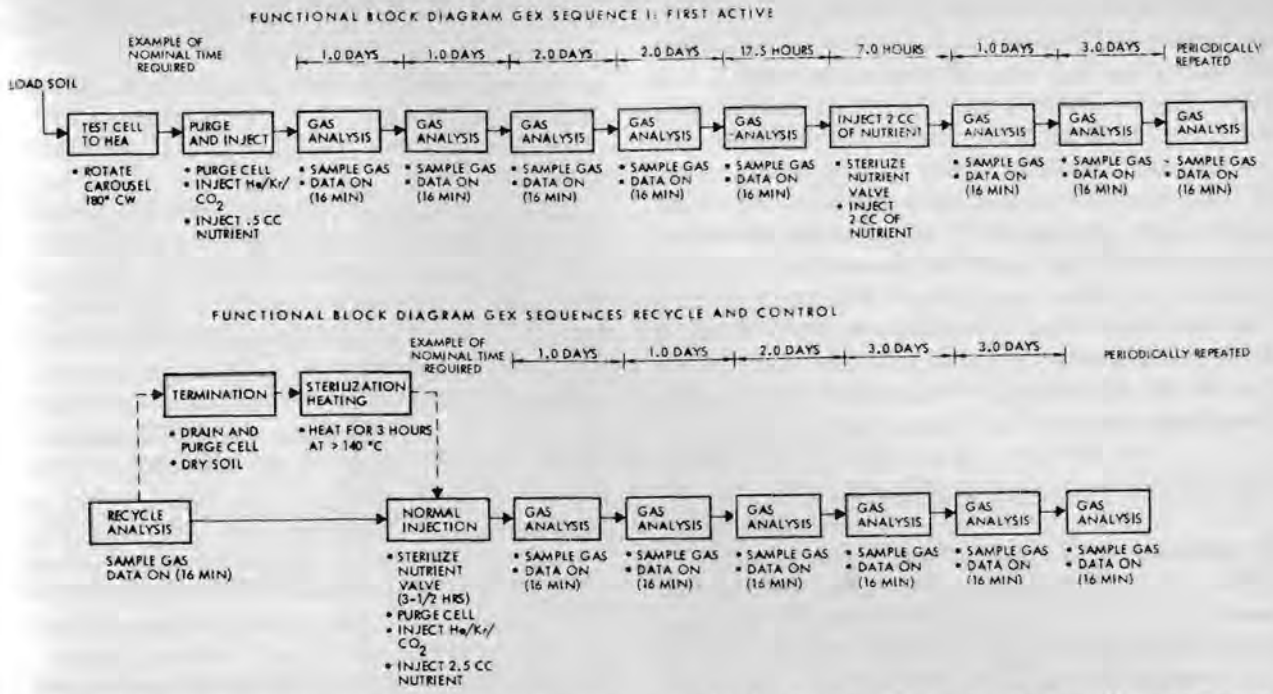

FIG. 20. Gas exchange experiment sequence diagramming the major events as blocks of activity. The top line illustrates the one time events of placing soil in the test cell and the humid analysis sequence. The bottom line presents the events which are repeated in each following analysis cycle.

(via S-23) and then opening drain valve S-27 for 1 min. This pressurization is repeated and S-27 opened again. He is allowed to flow at 2 std cm^3/min while S-27 is opened to purge the cell. S-23 is then closed, He excess pressure vented via S-27 and after S-27 is closed, fresh incubation gas and nutrient are injected, starting another incubation cycle. The basic GEx concept is the repeated incubation of one soil sample in order to provide opportunity for a growth response to occur and to help differentiate between biological and purely chemical responses. The system does have the capability of taking a second soil sample on top of the first in the single test cell if desired. The nutrient system was designed for four complete incubation cycles with the nominal amount of deliverable nutrient being about 13.5 cm^3 as compared to the amount used in one incubation cycle of 2.5 ± 0.5 cm^3.

If desired, a control incubation can be performed by first drying the soil and cell with flowing He while heating the cell and then sterilizing the soil by heating the closed cell at 150 °C for 3 h. After cooling the cell is purged, incubation gas and nutrient added, and the incubation and gas analyses conducted as before. A summary of the sequence as run on both Landers on Mars is given in Table IX.

The cell must also be dried prior to opening the test cell to acquire a second soil sample of that as desired. If the soil is not fully dry on cell opening, exposing the contents to Martian pressure, it could erupt because of rapid water volatilization and soil particles deposited on the cell seal could cause sufficient leakage to prevent subsequent successful incubation gas retention. The soil drying can be performed by either heating the cell in a He purge flow, or by maintaining incubation temperature while leaving the drain valve open a sufficient length of time (after an initial purge to remove the bulk of the nutrient).

Whenever nutrient is drained from the cell it is deposited in a sump in the common services module where it is slowly evaporated through a charcoal trap. In this manner the nutrient organic matter is retained in the sump or held on the charcoal to prevent organic contamination of the soil yet to be acquired from the surface and analyzed by the molecular analysis (GCMS) instrument.[23]

A test of the GEx experiment performance was conducted on Earth utilizing a complete instrument whose configuration was very nearly like the instruments now on Mars. The GEx results for that test which consisted of a humid mode, three cycles in the wet mode, and one sterilized soil wet mode are given in Fig. 21. Evidence for biological activity is not seen until after simulated Martian day 22 when CO_2 and N_2 are seen to increase and H_2 appears after the instrument has been exposed to room temperature for 7 days for repair. The conclusion that the gas changes are due to biological activity is reinforced by the dramatic CO_2 and H_2 increase in the third wet mode cycle. Final confirmation of biological activity is made in the sterilized soil mode where the previous vigorous gas evolution ceases. The soil used in this test was the Aiken soil described in Sec. V D.

Each point in the graph of Fig. 21 represents the results of one gas analysis performed on the gases above the incubating soil. Only one krypton point is given at the beginning of each new mode because the krypton

concentration is assumed to be unchanged by biological activity. Therefore all subsequent gas analysis data is normalized to the original krypton value.

On the Martian surface, the GEx experiment has conducted 9 months of operation on Lander 1 and 8 months of operation on Lander 2 (Table X). During that time three 1-cm^3 samples of soil were placed in the single test cell on each Lander, and 52 gas analyses performed on Lander 1 and 57 on Lander 2. In addition, Lander 1 performed two Mars atmosphere gas analyses and Lander 2 performed one. The GEx experiment operation ceased on both Landers in April 1977 with the consumption of all the 77 000 usable std cm^3 of helium from the carrier gas supply.

VIII. COMMON SUPPORT ELEMENTS

The Biology Instrument is packaged in two assemblies: the electrical subsystem (ESS) and the mechanical subsystem (MSS). The MSS contains the three experiments previously described and common support elements for the experiments. All elements of the MSS occupy a space of less than 16 500 cm^3 (19.8 × 27.7 × 30.0 cm). The contents of this small package include: 8 experiment test cells, 4 geared stepper motors, 6 thermally actuated isolation values, 39 latching solenoid valves, 5 supplies of nutrients or special gases, 1 regulated high-purity helium supply, 2 nuclear detection subsystems, 1 dual column gas chromatograph, 1 soil distributor assembly, 1 xenon-arc lamp, 43 heater elements, 4 thermoelectric coolers and heat pipes, 1 high-pressure pure helium gas supply, and 3 Geneva drive mechanisms for the test cell carousels. Additionally, there are traps, sumps, plumbing, wiring, and all other elements needed to implement the three biological experiments. The MSS is physically arranged as a group of separable and interchangeable assemblies, each of which were assembled and tested independently. These major assemblies consist of the following:

(1) Three experiment modules (labeled release, pyrolytic release, and gas exchange);
(2) A common services module (CSM);
(3) A soil distribution assembly (SDA);
(4) An interface module that attaches to the Viking Lander (the upper mounting plate assembly);
(5) A pyrolytic release illuminator assembly (xenon lamp);
(6) A nuclear detector module with its electronics.

After each of the above major assemblies have been tested, they are integrated to form a complete MSS. Because of the similarity of thermal control requirements, the experiment modules are grouped together along with the common services module which supplies pressurized gas to the experiment modules. The SDA, which meters out small soil samples to the three experiments, is suspended from the interface module (the upper mounting plate assembly) by an array of thin

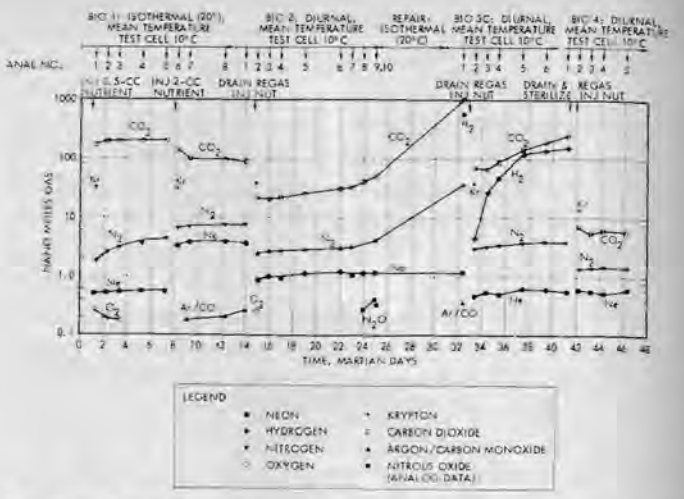

FIG. 21. Gas exchange experiment active and sterilized soil gas headspace composition. Data are from a ground test of Earth soil in a flightlike instrument and illustrate gas changes from living organisms which then disappear after heating the soil to inactivate the organisms.

titanium struts that provide thermal isolation and structural support.

The interface module includes the illuminator assembly which contains a xenon-arc lamp to illuminate the soil in the PR experiment test cell, and a series of thermoelectric cooler modules to maintain experiment incubation temperatures in the case of a "hot" landing site. The addition of the detector module completes this part of the mechanical assembly.

The ESS provides the power conditioning, data handling/conversion and storage, and the electrical and electromechanical control. A functional block diagram of the ESS is shown in Fig. 22. As can be seen from the figure, the ESS is organized by electrical function and not by experiment, allowing for extensive sharing of experiment common usage circuits. The total number of electronic parts within the ESS is 1880 of which a large percentage are medium and large scale integrated circuits. These components are mounted on

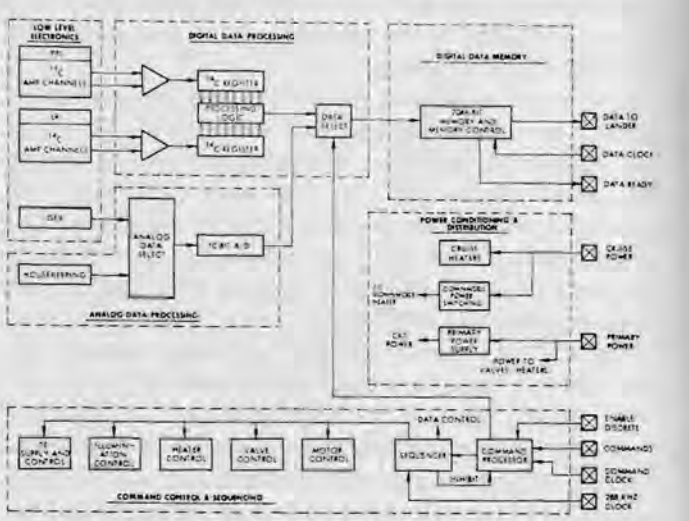

FIG. 22. Biology instrument electrical subsystem power and signal flow diagram.

12 multilayered printed circuit boards which are four, six, and eight layered, with interboard connections provided by over 4600 plated-through communication holes.

The ESS is designed to make maximum use of time-shared control and data handling circuitry while maintaining minimum interdependence among the three experiments. The ESS is functionally and mechanically divided into three sections (slices). The first slice (A1) contains all of the power conditioning and distribution circuitry. The conditioning is done with three separate power supplies operating from the two Lander power buses. The A2 slice contains the three experiment sequencers along with the instrument's command processor, buffer memory, and A/D converter. This slice also contains the GEx low-level electronics, housekeeping circuits, and the ^{14}C digital data processing logic. The third slice (A3) contains the MSS control and interface circuits. These consist of proportional and limit switching heater controllers, thermal isolation valve drivers, solenoid valve driver matrix, a four-phase stepper motor controller, and a heater preregulator.

Some electronics are located in the MSS in order to reduce susceptibility to generation of EMI. This includes the low level circuitry for the ^{14}C detectors, two electronic thermostat heater controllers, and the starting circuitry for the xenon lamp.

A. Electronic subsystem description

1. Power distribution and conditioning

The power conditioning is performed in the A1 slice. The instrument receives power from three buses on the Lander. They are

(1) *Bio operate*. This power bus supplied the primary power for the instrument. It is turned on after landing and provides for all power, except for the cruise/down-mode heaters and the thermo-electric coolers and has a voltage range of 24–37 V.

(2) *Bio thermal*. This power bus is applied to the instrument after launch and is used exclusively for temperature control of items that must be controlled when bio operate power is not available.

(3) *Bio emergency*. This bus will be turned on only in case there is a Lander power drop-out during the landed mission. The bus provides a power pulse which is used to close off the common services helium system and disable the power supply to the thermoelectric coolers.

The circuits are the primary power supply, the current inrush limiter, thermoelectric power supply, and the xenon lamp power supply. This slice also contains the master reset circuit, a proportional heater controller and two electronic thermostats (bang-bang limit switching heater controllers). The heater controllers, which are located in the A1 slice only for packaging convenience, are discussed later in the MSS control section. The remaining A1 slice circuits are discussed below.

Primary power supply. The primary power supply consists of a switching regulator and a 20-kHz power converter. The switching regulator produces a regulated +15 V from the bio operate bus. Its frequency of operation is determined by the load demand of the system and can rise to 50 kHz. This +15-V supply is then used to power the converter. The switching regulator takes its feedback from a separate winding on the converter. This feedback causes the +15-V line to raise or lower in order to maintain constant flux in the output transformer of the converter.

The 20-kHz converter uses a two-transducer oscillator based on a nonsaturating transformer. The frequency of the oscillator is directly proportional to the 15-V input from the switching regulator. The output transformer of the oscillator circuit has one winding which provides a source for the high voltage dc levels (200 and 170 V dc for the PR and LR modules) and another which provides drive for a square-wave power amplifier. This latter circuit uses the 15-V output from the switching regulator as a power source, and provides three sets of output voltages: one set of four voltages has a floating return and is used within the ESS, and a separate +5-V output which is the control voltage for the preregulator.

Master reset. The master reset logic signal (MR01) is used throughout the ESS to initialize the system. This logic signal is generated by a voltage comparator which senses the +5-V output of the primary power supply and thus the MR01 reset signal is produced whenever bio operate power is applied to the instrument. This signal resets all of the logic and causes all the system valves and latching relays to go to a known state.

In-rush current control. In order to protect the lander bus, a 2-Ω resistor is in series with the bio operate line to reduce filter in-rush current during the initial power turn-off. The circuit uses the MR01 reset signal to short the resistor with a latching relay contact 100 ms after power is applied. When the bio operate bus is removed, the relay is reset so that the 2-Ω resistor will be in the circuit when power is reapplied. A special relay driver, powered by the bio thermal bus is triggered by a phototransistor in an optical coupler which responds to a light pulse generated by a "voltage-going-down" circuit on the bio operator line.

Illumination control power supply. The illumination control power supply takes power from the bio operate bus and provides power and control for the xenon lamp in the PR illuminator assembly. The lamp is part of the pyrolytic release experiment and provides simulated Martian sunlight for photosynthetic incubation. In this circuit, a variable-frequency-chopper regulator controls the current drawn by the lamp. The control circuit error amplifier also accepts the lamp voltage as an input and uses this signal to modify the lamp current level such that lamp power is nominally constant (within 5%) over the entire operating range.

Lamp ignition is accomplished by supplying a voltage of ionizing potential (7.5–8.0 kV) to the lamp while the lamp supply is also attempting to draw high current through the lamp. This sustains lamp ignition and the

lamp voltage and current then drop to low steady-state values. A "lamp on" signal is generated during normal lamp operation for use within the logic circuts and for telemetry. Should the lamp extinguish inadvertently, bursts of eight lamp restart pulses are applied at 32-min intervals until it restarts.

Thermoelectric cooler power supply. The thermoelectric circuitry controls the operation of four Peltier-effect coolers used to cool the test cells during the hot portion of the Martian sol. The four coolers are operated in series by one control circuit. Temperature sensing is accomplished by a single thermistor, located on the GEx head end. The temperature set point (+12 °C) was selected to maintain temperature and prevent the coolers from operating while the incubation heaters are operating.

The power supply is a standard configuration switching ripple regulator with an inductive output filter. Once the circuit is commanded on, the power supply runs until it is overridden by the thermoelectric temperature controller. The temperature controller then modulates the power supply to maintain the desired temperature in the MSS.

The control logic for the thermoelectric controller enables or disables the circuit on command from the Lander GCSC. The bio emergency pulse returns the thermoelectric relays to the off state if the coolers are on when it appears.

2. Command, control, and data handling

All of the command, control, and data handling signals are produced by the A2 slice. The heart of the slice is the three experiment sequencers. These sequencers produce almost all of the control signals required by the instrument to perform the individual experiments. The sequencers are controlled by commands from the Lander and received by the command processor. After commands are operated on by the command processor, the information is stored in the buffer memory along with the other data requested by the sequencers. The memory receives its data from two sources. The first is from a 10-bit A/D converter. The converter is used to sample the analog GEx data and the temperature data. The other source of data is from the ^{14}C data processing logic which is used to accumulate the pulses produced by ^{14}C low-level electronics in the LR and PR experiments. All three experiments are synchronously independent of each other. The control is maintained synchronously through the use of a master clock generator which produces 14 phase-controlled clocks from the main Lander 288-kHz clock, allowing the three experiments to use the common circuits within the ESS on a noninterference basis. The circuits within this slice are described below.

Command processor. The command processor provides the command interface between the biology instrument and the Lander guidance command and sequencing computer (GCSG). Commands are 24 bits long and are sent from the GCSC in a serial NRZ code. The processor serves two functions in the Lander. One is to receive, decode, and execute distinct command functions, and the other is to provide access through the telemetry system to the three experiment sequencers.

The commands are received and held in a 16-bit shift register which utilizes serial loading (and readout to the memory) with parallel readout for decoding of the stored word. It provides the multiple functions of receiving the command word, holding it for verification and decoding, and providing temporary storage for the command word until the memory can accept it. All commands received by the instrument are stored in the memory whether executed or not. Although commands are 24 bits in length, the 16-bit register is long enough to store any command. The first 8 bits are not used internally to the biology instrument but are used by the Lander to trigger support measurements such as Lander bus current. The command decoding gates decode the leftmost 6 bits of the command holding register, which are the last 6 bits (bits 19 through 24) of the command word shifted into the register, as two subfields of 3 bits each. For each combination of bits within these subfields, a discrete command signal is generated. As mentioned above, bits 1–8 of the command word contain no information. Bit 9 is a parity bit for the 16-bit command word, and is a zero or one as required to achieve odd parity. For the commands which provide access to one or another of the module sequencers, bit 10 is a "flag" bit used to modify the effect of some sequencer commands, and bits 11–18 contain a sequencer address of a subroutine which is being called into execution. The pattern of bits 10–18 is sent directly to the referenced module sequencer when the appropriate command signals are decoded from the command subfields.

Master clock generator. The biology instrument is supplied with a stable 288-kHz clock from the Lander. The instrument uses this clock to derive all of its internal timing. Since no higher clock rate than the 288 kHz is required by the instrument, all timing clocks are produced by synchronous division of the Lander clock. The master clock generator produces 14 separate clock lines for the instrument control. The division is carried down to 2 pulses/h with the dominant clocks being 97 kHz and 1 pulse/min. The 96-kHz clock is used as the main control frequency and all data are moved internally at this rate. The 1-pulse/min clocks provide the main timing base for the sequencers.

A 2048-bit static sequential-access memory is designed around eight semiconductor devices, each of which is a 256 × 1 MOS random-access memory integrated circuit. The memory operates in three modes: (1) standby, where a minimum level of power is applied to the memory stack to retain stored information; (2) write, where the memory is organized to accept 12-bit data words from any of four data sources, attach a 3-bit ID tag and 1 parity bit, and store the resulting 16-bit word in the memory stack; and (3) read, where the memory will go into a read mode upon Lander

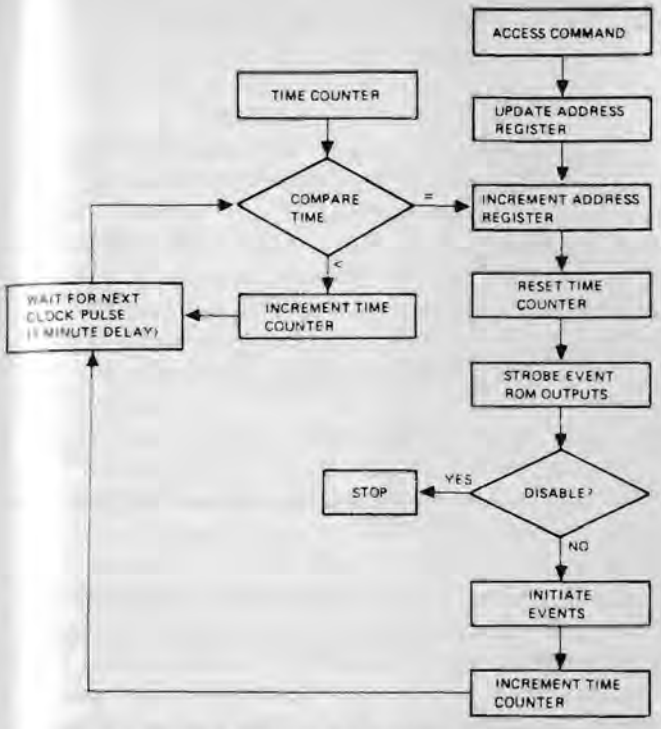

FIG. 23. Electrical subsystem simplified sequencer flow diagram.

command or when the memory is three quarters full. In read mode, the memory first generates a pseudo-random synchronization word and instrument ID for Lander data identification and frame data (frame number and number of words in memory) and then transmits the memory contents (first in, first out) to the Lander (DAPU). When empty, the memory reverts to the standby mode.

In standby mode, a counter within the data select and control function continually scans the write-cycle request lines and read-cycle lines looking for results.

Sequencer. The sequencer is the unit which controls the complete operation of the biology instrument. It is composed of three independent sequencers—one each of LR, PR, and GEx.

The operation and composition of the three sequencers are similar, each using microprogramming for operational control. The microprogramming is performed with the use of 256 × 10 MOS read-only memories (ROMs). The GEx and LR sequencers use three ROMs and the PR sequencer uses four. The ROMs for each sequencer are parallel addressed and thus provide 256 discrete program steps (words). Each program step provides 30 bits of information (40 bits for PR), which when decoded are used to control the internal operation of the sequence and provide event signals to the instrument. Events are command signals produced by the sequencers which cause valve operations, heater switching, etc. Each program step is subdivided into two microinstructions. The first is 10 bits long (one ROM output) and is used directly to provide time information for the sequencer. This instruction determines the time (in minutes) between successive events and has a range of 1–1024 min. The second microinstruction of each program step contains both control and event information as described below. This instruction contains 20 bits of information (30 bits for PR) and is decoded to produce the required signals.

A simplified signal flow diagram of one of the experiment sequencers is shown in Fig. 23. The sequencer operation is initiated with the receipt of an access command from the command processor. The command is 9 bits long with 8 bits representing a ROM address, the ninth being a "flag." The command is parallel loaded into the ROM address register thus providing access to any subroutine stored within the ROMs. The sequencer control circuitry is then activated and the address register is incremented by one count and time counter is reset to zero. The outputs of the event ROMs are then decoded and strobed to produce the event and control signals. If a sequencer disable signal is decoded, the sequencer immediately shuts down. When the sequencer is disabled, it remains dormant until a new access command is received. If the event word (second micro-instruction) does not contain a disable command, the information it does contain is decoded and those events are sent to the system. After the events are initiated, the timer counter is incremented by 1 bit and a delay occurs, typically 1 min. The 1-min delay is the period of the 1 ppm (100 ms) clock the sequencer uses for its time base. After the delay, the output of the time ROM (first microinstruction) is compared with contents of the time counter. If they are not the same, the time counter is incremented by one count and another 1-min delay occurs. The time comparison loop cycles until the output of the time ROM matches the time counter contents. When this occurs, it is time for the next event to occur. The sequencer proceeds to increment the address register and continues to process the next instruction. The sequencer will continue to operate in this manner until it finishes the subroutine and disables itself or is commanded by the Lander to stop or change subroutines. Each sequencer also has a data subroutine which it calls on for long periods of repetitive data sampling. The PR and LR subroutines cause the respective ^{14}C data counts to be sampled along with the associated detector temperatures once every 16 min. The GEx subroutine when activated causes the output of the GEx LLE to be sampled at a rate of 1/s for the duration of a chromatogram.

Temperature monitor buffer amplifier. Six temperature bridges, using platinum temperature sensors, are monitored selectively through analog FET switches, amplified and sent to the A/D for processing. Selection of the desired bridge and temperature range is determined by input commands received from the sequencers. At the same time, the output FET switch is activated, selecting the amplified bridge signal to transfer it to the A/D converter.

The temperature range monitored is from −20° to 780 °C. The two temperature ranges of interest are −20° to 200 °C for ambient and sterilization temperature measurements and 500 °C to 780 °C for PR activities.

There are no temperatures to be monitored between 200° and 500 °C; therefore, this range is bypassed. Specific temperatures measured by the platinum sensors include the three test cells, GEx column and detector temperatures, and the PR organic vapor trap temperature.

Two thermistors mounted on the ^{14}C detectors are also monitored but need no amplification. These voltages are fed through the output analog switches to the A/D processing and are selected in the same way as the platinum sensors.

Test cell position monitor. The test cell position for each of the three experiments is detected by the use of optical sensing. In each experiment module in the mechanical assembly, the test cell can be rotated to as many as six positions by the use of a geared stepper motor coupled to a Geneva wheel. This Geneva wheel is mounted to a shaft at the center of rotation on the test cell assembly.

The test cell position monitor (TCPM) uses light emitting diodes and phototransistors to detect the six positions of a Geneva wheel for each of the three experiments. Light from an LED which passes through a 1.52-mm hole in the Geneva wheel is detected by a phototransistor. The two elements are separated by 4.57 mm maximum. To read six positions, three LEDs and three phototransistors are used, and each position is binary coded to give a unique indication. The binary numbers 000 and 111 are not used for positions because a 000 would not be distinguishable from a solid part of the Geneva (i.e., no holes or slots to read through) and a 111 output is not distinguishable from a Geneva wheel slot. Each TCPM has three LEDs and three phototransistors, so that 9 bits of TCPM data are available.

GEx low-level electronics. The function of the GEx low-level electronics (LLE) circuit is to measure the difference in thermal conductivity between gases passing through detector cells at the ends of active and reference gas chromatograph columns and to make the information available to the analog-digital converter through the multiplexer.

A block diagram of the GEx LLE, Fig. 24 gives a representation of significant features. Inasmuch as the gas chromatograph (GC) is a "differential" device, balance between the active and reference sides is very important. The figure shows two thermistors at the input of a differential amplifier. Each thermistor operates in its own bridge circuit, powered by an operational amplifier, such that bead resistance is held constant. The output of the preamplifier differential op-amp applies the difference signal from the beads to the summing input at the next stage with a gain of 50. The gain-of-two summing amplifier is the main output amplifier for bead signals over 5 mV. For smaller signals, another gain of 10 is applied by the autoranging stage. A reference circuit monitors the output of the last stage and operates a switch (FET) to connect the output line to the summing amplifier when the last stage output voltage is greater than 5 V. The autorange comparator generates a logic signal which is included in the GC output data to signal which gain setting is being used.

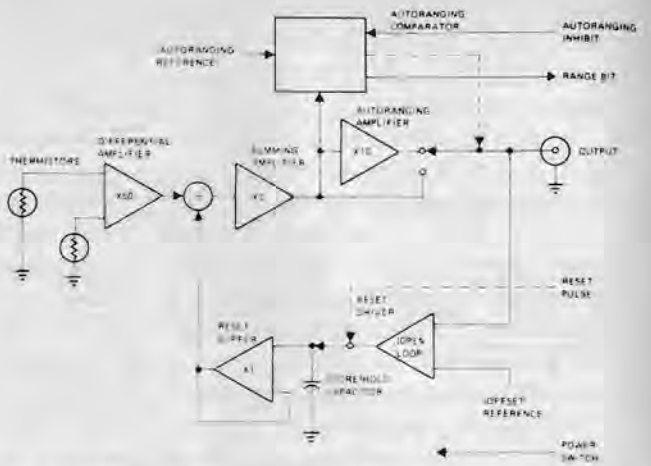

FIG. 24. Gas exchange experiment chromatograph detector low level electronics block diagram.

An integrating offset control is incorporated in the circuit. Upon receipt of a reset pulse, the switch is closed between the output of the reset driver and the holding capacitor. When this happens, the feedback circuit around the reset driver is all the rest of the circuit including the reset buffer, the summing amplifier, and the autoranging stage. The reset driver then charges the holding capacitor to that voltage at which the output voltage is equal to the offset reference (approximately 500 mV) regardless of the instantaneous value of the signal from the differential amplifier. On termination of the reset pulse, the reset switch is opened and the holding capacitor retains its value, thus holding the output at the offset reference from which the differential amplifier signal may now cause it to vary.

Analog-to-digital converter. The instrument A/D converter uses dual slope integrating techniques to achieve its required accuracy. The converter has a 10-bit resolution with an accuracy of ±0.11%. Since the instrument analog data change very slowly, aperture time was not important and a large integrating time constant was used to reduce noise errors.

When a conversion cycle starts, the converter first activates an offset correction loop to eliminate converter biases in the data. The input is applied to the integrator for a full 1024 pulse clock period. An accurate negative reference voltage is then applied to the integrator while a counter is accumulating 288 kHz clock pulses. When the integrator output crosses 0 V, the counter input is cut off and its contents are transferred to a shift register. The converter then adds 2 bits of identification to the 10-bit converted work and the 12-bit word is sent to the memory.

Mechanical subsystem control. The valves, heaters, and motors in the MSS are controlled from the A3 slice. The MSS contains 6 thermal isolation valves, 39 latching solenoid valves, 4 stepper motors, and 43 heaters. The heaters are controlled either by mechanical thermostats, electronic thermostats, or proportional heater con-

trollers. All heaters and solenoid valves run from raw bus voltage in order to reduce conversion efficiency losses. Because of the wide variation in the voltage bus (24–37 V), the proportional heater controllers require a heater preregulator. The preregulator along with the other MSS control circuits are described below.

Valve control. The 39 latching solenoid valves are controlled by a 6 × 7 driver matrix. Since the valves run from raw power, the control voltages for the drivers were isolated. The drivers used in the matrix are relays which not only provide the required isolation but also allow bidirectional current flow to the valves to latch and unlatch them.

The circuit receives 100-ms pulse signals from the valve driver logic which operate nonlatching relays by applying 30-V power from the ESS power supply to the relay coils through hybrid drivers. The relays enable bio bus power to be applied to the valve coils. By energizing the proper two relays using two logic signals from the valve driver logic, one valve is selected through the 6 × 7 diode matrix. An auxiliary relay, whose state depends on a third logic signal, is used to establish whether the selected valve is to receive a voltage pulse in the OPEN or CLOSE direction. One of the pair of matrix-selection logic signals is also used to enable the bio bus pulse relay driver. The pulse is gated by master clock pulse with duration of 50 ms, delayed 25 ms from the start of all the "100 ms" clocks. The result is that the bio bus relay is closed for 50 ms in the middle of the logic pulses which select a relay and determine the voltage pulse direction. This assures that the valve-select relay contacts are closed and settled before and after the current pulse is transmitted.

Motor control. The motor control circuit operates the stepping motors for the soil distribution assembly (SDA) and three test cell positioning mechanisms (TCPM). The circuit thus controls four stepping motors of which only one may be operational at any given time. This constraint permits much of the motor control circuitry to be shared by all of the motors resulting in a substantial reduction in both parts count and power requirements.

Upon receipt of a command from the sequencers (for the TCPM) or from the command processor (for the SDA), the controller turns on the appropriate motor power switch. It also generates a four-phase 20-Hz stepper sequence which, through driver switches, causes the motor to step in the appropriate direction. As the motor is stepping, the controller is constantly looking for two position feedback signals. The first signal allows the controller to act upon the second for the TCPM and, for the SDA, causes the step sequence to reverse and thus the motor direction to change. The second feedback signal commands the motor to stop and the controller to shut down. The position feedback signals are generated by optoelectronics in a manner similar to the TCPM monitor described earlier. A full motor operation for the TCPM requires 12 s while a complete SDA cycle requires 24 s. The SDA has a second mode of operation in which the motor is sequentially stepped twice in one direction and twice in the other to provide a vibration in the SDA soil cup.

Isolation valve driver. The isolation valve driver operates only once during the mission—during the landed initialization sequence to access the stored gas supplies. It is activated by a Lander command and uses a counter and driver to sequentially apply +15 V to the system TIV's for either 3 or 5 min, depending on the specific TIV thermal load.

Heater preregulator. The heater preregulator works with the proportional controller to provide power to nine proportionally controlled heaters in the instrument. Power is supplied as a train of rectangular voltage pulses at a fixed frequency of 2 kHz. The duration of each pulse is a function of controlled temperature, heater temperature command, and the actual value of the voltage on the bio operate power line (between 24 and 37 V). The actual pulse duration is computed as a product of two ratios: the first is the duty cycle of ramp and gate signals generated by the heater preregulator as a function of bus voltage; the second ratio is the fraction of ramp time occupied by the heating pulse for each heater, as determined by its respective proportional controller from temperature sensing feedback.

The function of the preregulator is to make the maximum power taken from the bus nearly independent of bus voltage. With this accomplished, the loop gain requirements on the control circuits are minimized, peak power from the bus is reduced, and temperature rise requirements on heaters can be easily met by sizing of the heaters, based on constant power input.

The preregulation is accomplished by generating a ramp and an accompanying gate signal of constant amplitude and with a duty cycle such that a resistive load switched to the bus at the resulting duty cycle would draw the same power at 24 V bus voltage as at 37 V. Available power to the same load at intermediate voltages is slightly less with a minimum of over 92% of end-point values at 30.5 V.

Heat controllers. Three methods of heater control are used for thermal control. The simplest is with mechanical thermostats. These thermostats are located in the MSS on the thermal masses they are controlling and are powered either from the bus or through latching relays within the ESS. The second method of control is with electronic thermostats. These "bang-bang" (limit switching) controllers use thermistors for temperature feedback and are used where mechanical thermostats will not fit or where tighter temperature control is required. The electronic thermostats are capable of controlling to ±1 °C and are powered from the raw bus through latching relays. The instrument contains five electronic thermostats.

The third and most accurate controllers are proportional heater controllers. These controllers use pulse width modulation at 2 kHz from the heater preregulator to control nine of the main system heaters. The proportional controllers power the heaters directly from the

bio operate bus. The output drive stage of the controllers is isolated with optically coupled isolators from the error amplifier and ramp comparator electronics. The proportional controllers have as many as five control temperatures per controller ranging from 24° to 725 °C with the selected temperature being commanded by the experiment sequencers. The proportional controllers use platinum wire sensors for temperature feedback.

3. MSS electronics

The MSS also contains two electronic modules. These are the ^{14}C low level electronic (LLE) circuitry for the PR and LR experiments and the high-voltage starting circuit for the PR xenon lamp. The LLE circuitry consists of four separate channels each of which is mounted on a two-sided PC board. The boards are in turn mounted in a machined aluminum housing along with the ^{14}C detectors. The xenon lamp starting electronics are also mounted on a two-sided PC board and packaged in the xenon lamp housing module. Both circuits are mounted in the MSS because of electromagnetic interference (EMI) considerations. The LLE has extremely high gain and must be located as close as is physically possible to the ^{14}C detectors to reduce EMI susceptibility. The lamp starting circuit has the reverse problem in that it produces a great deal of EMI when the lamp arc is being struck.

Low-level electronics for nuclear detection subsystem. Two of the experiments rely on the assumption that life processes in Martian organisms will assimilate nutrients or gases which have been labeled with radioactive carbon-14. Detection of the ^{14}C (which is a beta emitter) is accomplished with the use of silicon diffused-junction detectors.

Each of the four detectors (two for PR and two for LR) has a low-level electronic channel dedicated to it. Except for channel gain levels associated with individual detector parameters, the LLE channels are identical. The channels consist of a charge sensitive amplifier (CSA) followed by a pulse shaping amplifier and an energy level discriminator.

When an electron emitted by a ^{14}C disintegration strikes the silicon detector, a charge transfer takes place between the detector and the CSA. The CSA then produces an output pulse whose amplitude and width are proportional to the energy of the particle detected. This pulse is coupled into a double differentiation, double integration pulse shaping amplifier, and then applied to the input of a double-ended voltage level discriminator. The discriminator produces a 10 μs output pulse to the ^{14}C data logic whenever the output pulse from the shaping amplifier is between two preselected voltage levels equivalent to an energy range of 34–85 keV. The discriminator thus disregards signals caused by particles with energies outside the range of most ^{14}C electrons.

Xenon lamp starting circuit for PR illuminator subsystem. In order to ignite the xenon lamp used in the PR experiment, the lamp must be ionized by high voltage and then have the ignition current sustained. The high-voltage ionizing pulse is provided by a trigger transformer and driving circuit which are located in the actual lamp assembly.

The primary of the trigger transformer has a high-voltage capacitor in series with it. In parallel with the transformer and capacitor is a silicon controlled rectifier (SCR). The capacitor is normally trickle charged to +200 V through a high-value resistor. When the lamp is to be ignited, a trigger pulse is sent from the lamp power supply in the ESS. This power supply provides the sustaining lamp power. The trigger pulse is used to turn on the SCR and dump the capacitor charge. This energy then flows through the transformer primary and causes a minimum of 7.5 kV to appear at the secondary winding and thus across the lamp electrodes.

In actual operation the voltage seldom rises above 5 kV since the xenon lamps ionize at that voltage and cause the secondary output voltage to collapse. Once the lamp is ionized, the lamp power supply sustains the arc by supplying the lamp with a constant 6.1 W of power at approximately 550 mA.

B. Hydraulic and pneumatic systems

The multiplicity of flow and pressure requirements for the various liquids, vapors, and gases to and from the experiment modules led to the development of numerous components and assemblies utilizing commonality of designs and hardware. Requirements for low leakage (10^{-6} to 10^{-8} std cm^3/s helium), large range of pressures, low weight, tight pressure regulation bands, and accurate flow metering resulted in hydraulic and pneumatic systems constructed primarily of (1.6 mm o.d.) stainless steel tubing. The design and operation of these systems are described below. The system flow schematics are shown in Figs. 5, 10, and 16.

1. Common services module

The common services module (CSM) contains the helium reservoir which provides energy storage for pneumatic actuators, a carrier gas for the gas chromatograph, a nutrient pressurant and purge gas for the LR and PR experiments, and the waste management system for the instrument. Major components within the CSM include the carrier gas supply, the high-pressure helium manifold, the low-pressure helium manifold, and the liquid vent system consisting of the liquid sump and the charcoal trap. An exploded view of the CSM is shown in Fig. 25.

Carrier gas supply. The carrier gas supply consists of a high-pressure spherical bottle welded to a manifold to which are attached an isolation device, filters, pressure regulators, pressure relief valves, and gas outlet tubes. The mounting lugs are integral with the manifold. A pressure sensor and a fill and drain valve are remotely located upstream of the bottle.

Prior to the flight phase of the Viking Mission, the helium reservoir was filled with a usable 77 000 std cm^3

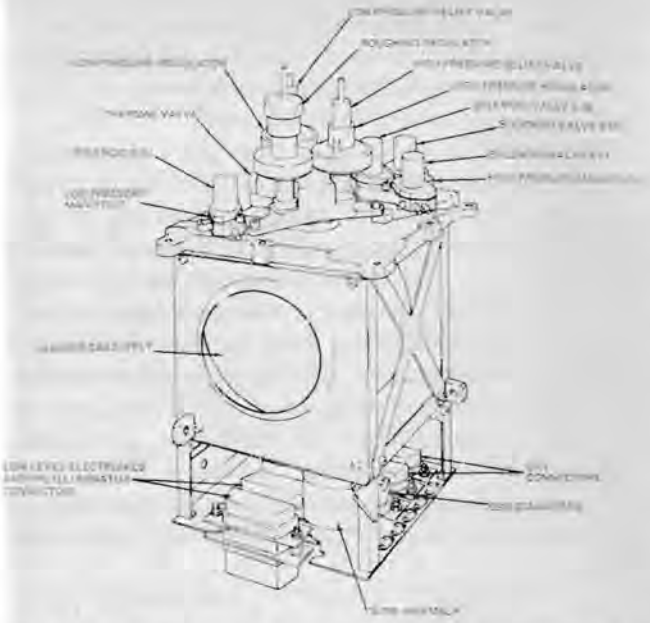

FIG. 25. Common services module. The major features are shown but the gas lines and electrical wiring are omitted for clarity.

of helium (99.999% pure) at a pressure of 315 kg cm^{-2} through a fill and drain valve. After the correct charge was achieved, the tubular extension was welded closed. Gas bottle pressure is contained by the thermal isolation valves. The isolation valves use a thermal actuator to pierce a diaphragm, opening a path for gas from the bottle to the roughing regulator by way of a 10-μm (absolute) filter. The roughing regulator reduces bottle pressure to 10.2 bar and two regulators downstream reduce the pressure to 9.2 and 1.2 bar, respectively, above ambient. If for any reason pressure at either outlet rises above its regulator setting, pressure relief valves will limit the rise to a maximum of 11.2 and 1.9 bar, respectively.

Instrument vents. The common services module, in addition to containing the carrier gas supply (CGS), also is the central location for all the vent systems for the biology instrument. These vent systems include both gaseous and liquid systems. The three gas vent systems, which are shown on the schematic as V1, V3, and V4, are used to vent helium gas from the instrument. The V1 vent is used for venting of the PR detector, the vertical actuators, the gas chromatograph system and the high-pressure manifold. The V3 system was designed for minimum resistance within the biology instrument to minimize vent diffusion times for the PR cell system and the gas exchange gas sample loop.

All liquids from the biology instrument are vented through the V2 vent system. Key element of this system is the sump, which operates by heating the liquid in the sump to about 40 °C and thereby converting it to water vapor prior to exhausing it to the Martian surface.

2. Miniature latching solenoid valves

Control of gaseous, liquid, and vapor flow within the experiment is performed by 39 miniature latching solenoid valves distributed throughout the three experiment modules and the common services module. Requirements for low-power, low-weight, low-leakage, and high reliability led to the development of a miniature latching solenoid valve weighing less than 9 g (Fig. 26).

The valve is operated by applying a 50-ms pulse at 28 V dc (nominal) to the coils of the miniature latching solenoid valve. The valve will latch open or closed, depending on polarity to the valve coils. A summary of performance characteristics is presented in Table XI. Five configurations of this valve are used to match the thermal and operational requirements of the experiments: basic valve with Viton E60C poppet, modified valve with ethylene propylene terpolymer (EPT) poppet, modified valve with Teflon poppet, diaphragm valve with EPT diaphragm seal (vented), and diaphragm valve with EPT diaphragm seal (unvented). The Viton valves are used

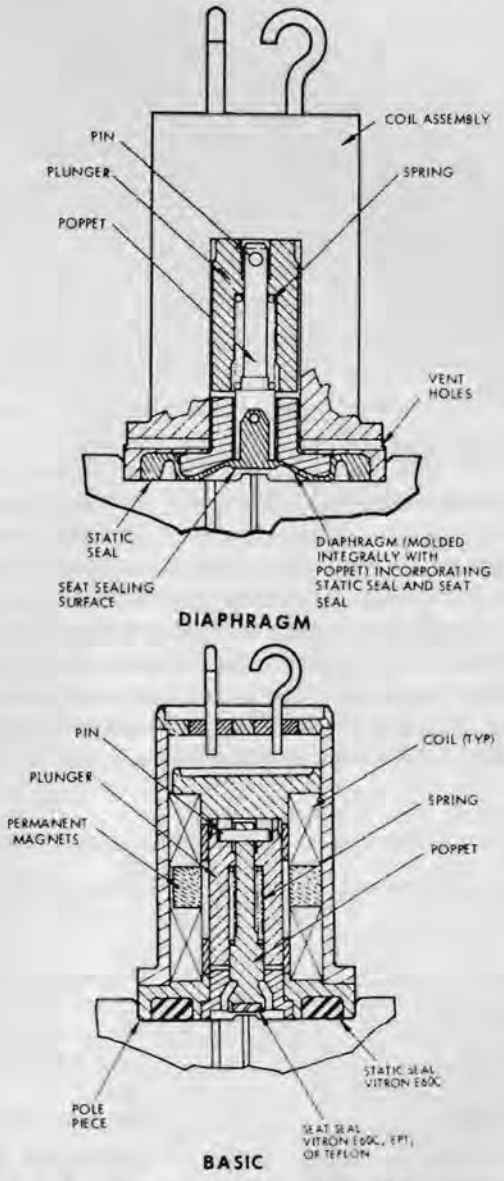

FIG. 26. Cross section of two configurations of the miniature latching solenoid valve. The diaphragm version incorporates a single-piece molded poppet and static seal which is not present in the basic version. This seal prevents any liquid or gas from reaching the sensitive area of the poppet and plunger.

TABLE XI. Physical and operating characteristics of the miniature latching solenoid valve.

Weight	8.7 g
Coil resistance	110 Ω
Latching force	0.726 kg
Dynamic seal load	0.272 kg
Total stroke	0.28 mm
Minimum opening voltage	11.8 V dc
Minimum closing voltage	13.4 V dc
Open response time	0.9 ms
Close response time	1.6 ms
Pressure drop	<0.38 mm orifice with $C_v = 0.65$
Reverse cracking pressure	>24.5 kg cm^{-2}
Burst pressure	>49 kg cm^{-2}
Internal leaking (std cm^3/s He)	1.5×10^{-7} to 5×10^{-4} depending on seat material configuration
External leakage (std cm^3/s He)	1×10^{-6}

where low leakage rates are required and the operational temperature ranges between −12° and 50 °C. The EPT valves are used where low leakage rates are required and the operational temperature ranges between −20° and 150 °C. To avoid poppet stiction, Teflon valves are employed in the V1 and V2 vent systems, the only locations where the valves are closed during instrument sterilization and Earth–Mars transit. In special applications in the LR and GEx nutrient systems, the diaphragm valves are used to separate the nutrient from the miniature latching solenoid valve internal parts which are nickel plated (in GEx because of toxicity concern) and to prevent corrosion of the LR incubation system vent valve (alternately wet/dry with nutrient).

3. Thermal isolation valves

The isolation device selected for the instrument gas and vapor reservoir systems is a thermally actuated diaphragm piercing valve. This device was chosen because of the requirement for greater than 2 years storage with negligible leakage. Principal features leading to its selection over a pyrotechnic device are simplicity, reliability, low weight, low peak power, and absence of combustion gases detrimental to experiment functions. Six thermal isolation valves are utilized in each biology instrument. The locations and designations of the thermal isolation valves are given in Table XII. All of the thermal isolation valves are actuated on Mars during the initialization sequence.

TABLE XII. Summary of the locations and purposes of the thermal isolation valves.

Experiment location	Burst disk thickness (μm)	Stored gas/vapor
Pyrolytic release	76	H_2O
Pyrolytic release	76	$^{13}CO_2/^{14}CO$ at 525 millibars
Gas exchange	76	$He/Kr/CO_2$ at 8.5 bars
Common service module—two used for redundancy	152/102	77 000 std cm^3 He at 306 bars (99.999% pure)
Gas exchange (located in LR module)	76	$He/CO_2/O_2$ at 8.5 bars (GCAA rejuvenation)

The thermal isolation valve (Fig. 27) is comprised of a thermal actuator and a burst disk of 0.076, 0.1, or 0.15 mm thickness. The 0.076-mm disks are used for reservoir supplies pressurized at or below 10.5 kg cm^{-2} and the thicker disks are used in the 315 kg cm^{-2} helium supply. When the thermal actuator is activated approximately 9 W of heat is transferred from the heater element to the thermal actuator case, silicone oil, and the surroundings. Heat transferred to the oil causes it to expand and drive the plunger through the burst disk. The plunger automatically retracts during cooldown, being driven primarily by the compressed bellows. In high-pressure applications, the retraction is assisted by the pressurized medium.

4. Lines and fittings

The nutrient gas supply and vent lines are all 304 or 316 stainless steel, 1.6 mm o.d. by 1.1 mm i.d., except for:

(1) LR detector line—3.2 mm o.d., 0.25 mm wall,

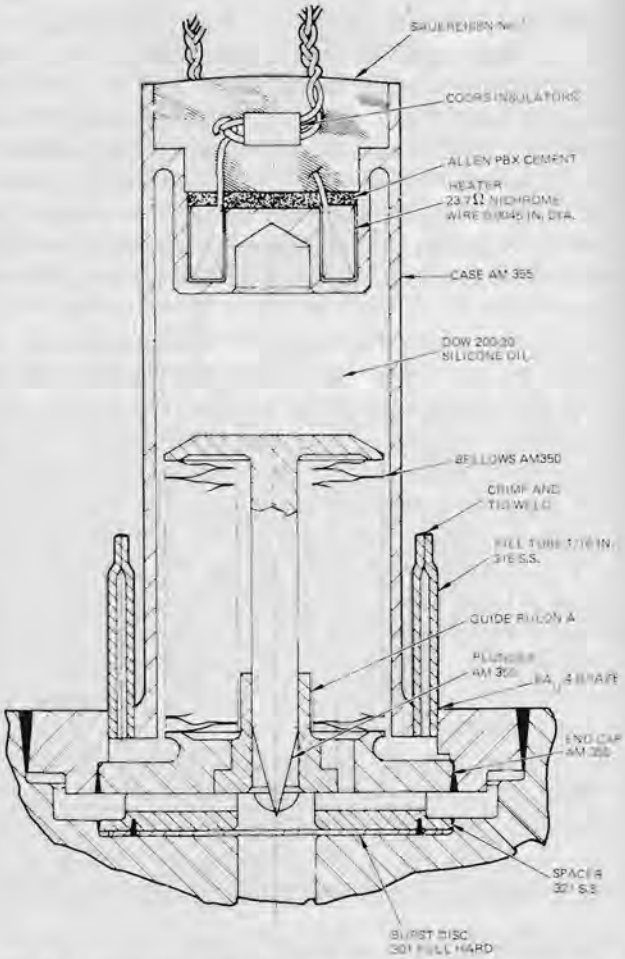

FIG. 27. Thermal isolation valve. The valve is composed of the thermal actuator which forces a pin through the burst disk to release the stored gas.

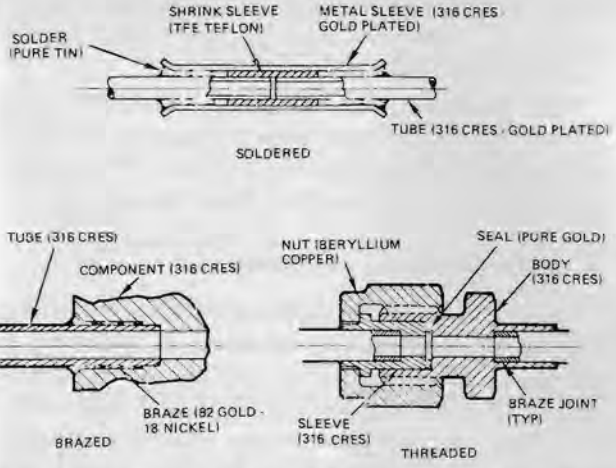

FIG. 28. Cross section of the three tube joints used in the biology instrument.

(2) High-pressure (315 kg cm^{-2}) lines—1.6 mm o.d., 0.43 mm wall,

(3) Various restrictors in the helium, nutrient, and vent systems, and

(4) Flexible Teflon lines in the vent system.

Methods of joining the tubing to valve blocks or other tubes are illustrated in Fig. 28. All joints are proof tested to 40.6 kg cm^{-2}, capable of sealing at 1×10^{-8} std cm^3 s^{-1} atm helium and compatible with biological requirements (toxicity). The high-pressure lines within the (315 kg cm^{-2}) CSM are welded using the tungsten inert gas technique.

C. Nuclear detection subsystem

Both the LR and PR experiments use radioactively labeled carbon as a detection mechanism for the experiment functions. Detection of the radioactive carbon in gaseous form such as CO_2 or CO is the role of the nuclear detection system.

For LR (Fig. 29), two solid state detectors view a fixed volume connected to the LR cell head space volume. Since the detection mechanism of the LR experiment is the measurement of radioactively labeled gases, the detectors respond to the radioactivity-labeled carbon contained in these gases. The signal, in the form of pulses from these detectors, is amplified by a charge amplifier, shaped, and then passed through a discrimination window (discriminator) for transmission to the electronic

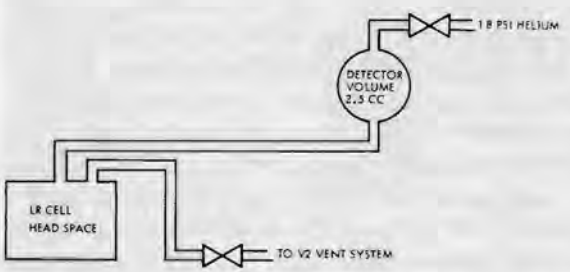

FIG. 29. Labeled release experiment radiation detection system functional block diagram.

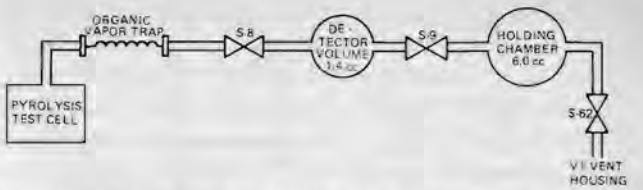

FIG. 30. Pyrolytic release experiment radiation detection system functional block diagram.

subsystem. Each of the two detectors has separate channels of electronics with the outputs summed into an accumulator located in the ESS. The output of the detection system is in the form of pulses whose average rate is a direct measure of the quantity of radioactive gas within the detector.

The detectors and electronics are similar for the PR experiment. The process (Fig. 30) is, however, different in that PR uses the 1.26 kg cm^{-2} helium gas to push the $^{14}CO_2$ into the detector and then closes off the detector and counts a fixed volume.

The detectors measure the betas emitted by radioactive $^{14}CO_2$ which have energies up to 156 keV. This task must be accomplished in the presence of a fairly high level of relatively low-energy flux from the radioisotope thermal generators on the lander, and in the presence of a small continuing flux of high energy cosmic rays. The thickness of the solid state detectors is optimized with respect to these considerations so that the ^{14}C beta particles have a high probability of capture within the detector and effective use can be made of a "counting window" to discriminate against the two principal sources of background. At low energies there is the exponential noise which is a function of the system noise level. Figure 31 is a graphical representation of the particle interactions with the silicon crystal, and the counting rate considerations which were used to determine the lower and upper energy levels (34–85 keV) of the counting window.

Since the energy from radioactive decay follows a Poisson distribution, the detectable limit of the signal is a function of the background from the RTG's and the time over which the signal is counted. The background

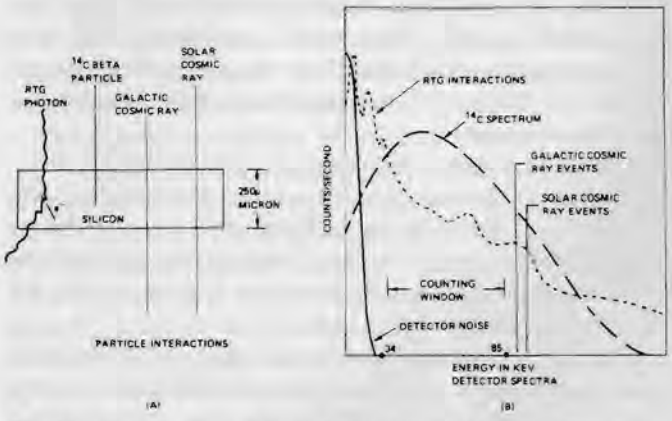

FIG. 31. Particle interactions with the carbon-14 detector silicon crystal and the energy spectrum within the detector of the carbon-14 signal and the various noise sources.

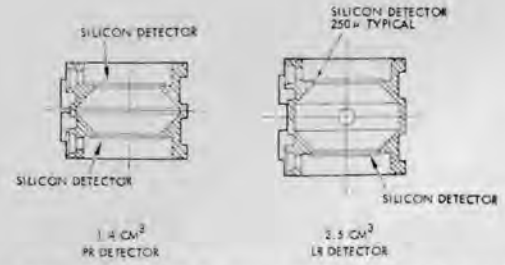

FIG. 32. Cross section of the pyrolytic release and labeled release experiment carbon-14 detectors.

from the RTG's was found to be between 400 and 500 counts per minute as seen by the detectors. These counting periods vary from 19 min in the case of the PR first peak (10^3–10^5 cpm expected) to several hours for the second peak (10 cpm is the minimum requirement). These counting periods must therefore be of sufficient duration to detect the above levels from the background. The background periods before and after the actual data counts should be of similar duration.

Diffused-junction silicon 250 μm thick is used as the active element for the detectors. These silicon sensors are operated with a reverse bias of 180 V applied to a small guard ring surrounding a 1 cm^2 active area. The active area receives its bias through the impedance between the active area and the guard ring. The normal leakage current is 0.2 A. Figure 32 shows a cross section of the two detectors.

Charged particles ionize the silicon and the ions in the active volume are collected as a charge proportional to the energy deposited in the active volume. This charge is amplified by the hybrid charge sensitive preamplifier giving a pulse whose height is proportional to the energy deposited. A hybrid shaping amplifier with time constants to minimize system noise is used to shape and amplify the signal pulses. Those pulses with heights between the nominal values of 0.8 and 2.0 V, corresponding to 34 and 85 keV energies, respectively, are then accepted by a hybrid window discriminator. A 5-V pulse is produced for each accepted pulse. These pulses are counted by accumulators in the ESS.

The 250-μm thickness of the silicon is large enough to absorb more than 85 keV for minimum ionizing particles. High-energy radiation from the RTGs is thus discriminated against. The maximum energy ^{14}C beta particles striking a silicon diode are stopped by 168 μm of silicon. Of the ^{14}C beta particles striking the silicon 56% are counted.

The geometry of the detection chambers has been optimized with respect to the overall detection efficiency. For the LR experiment a 2.5-cm^3 cylinder closed at both ends by the 1-cm^2 active area of the silicon diodes provides the optimum efficiency. The PR detector is 1.4 cm^3 in volume.

The detector body is made of Kovar (Fe–Ni–Cu) with feedthroughs and stainless steel tubes brazed to the body. The electrical feedthroughs are molybdenum pins, ceramic insulator, and Kovar tubes. The two silicon sensors are soldered in place to enclose the detection volume. Gold-plated Kovar covers are then soldered to the Kovar body to hermetically enclose the moisture sensitive side of the sensors.

The full-width half-maximum (FWHM) noise, as measured with a 60-keV pulse, averaged 5.38 ± 0.92 keV FWHM with a maximum of 6.47 keV FWHM for the silicon detectors in the three flight instruments.

D. Soil distribution assembly

The Lander's soil acquisition processing and distribution system provides the required soil samples to the biology instrument. The SDA within the instrument accepts, delivers, and meters the soil samples for each of its test chambers and stores sufficient quantities of each soil sample delivered such that a second distribution may be made to each of the three experiments. If not required for further experiments, the excess soil is transferred to soil dump cavities which are part of each experiment module. An exploded view of the SDA is presented in Fig. 33.

The SDA is capable of accepting, delivering, and metering soil with particle sizes up to 3870 μm and a volume of 6 cm^3. The instrument soil hopper is in position to receive soil from the Lander at all times except during the actual distribution of soil to the experiment test cells. The instrument meters and delivers the active soil samples to the individual experiments following a distribute soil command from the guidance control and sequencing computer. Prior to receiving a new soil sample, the unused soil is dumped into dump cells by cycling the SDA with dump cells under each experiment's soil load port. The order of soil delivery is gas exchange (1.00 cm^3), pyrolytic release (0.25 cm^3), and labeled release (0.50 cm^3).

E. Thermal design subsystems

The science objectives of the three experiments on the Lander together with equipment operational characteristics impose a wide range of requirements to be satisfied by the thermal subsystem. These requirements range, in the extremes, from 725 °C (PR experi-

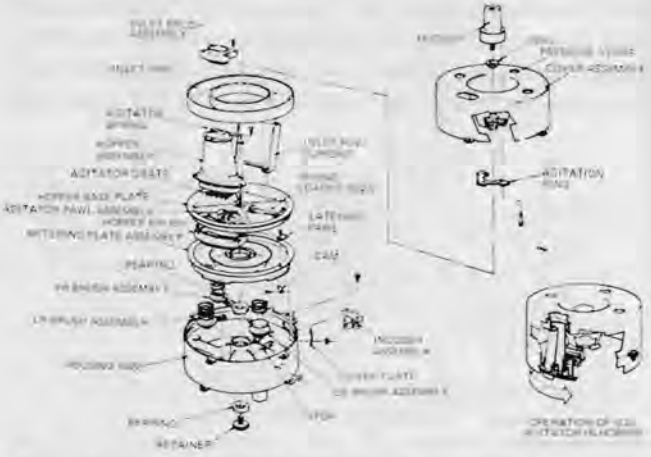

FIG. 33. Exploded view of the soil distribution assembly.

TABLE XIII. Summary of the major elements of the biology instrument thermal control system.

Control mode	Element	Function
Active	Heaters	Maintain cell temperatures above 5°C during incubation
	10 proportionally controlled (9 controllers)	Maintain liquid component temperature above freezing
	7 electronically controlled (5 controllers)	Perform control sterilization
	23 mechanical thermostat or sequence controlled	Perform analysis heating function
Passive	Thermal isolators/standoffs	Minimize heat losses
Passive	Component location	Control heat transfer between components
Passive	Surface emissivities	Control heat transfer between components
Passive	Convection/radiation shields	Minimize component heat losses
Active	4 thermoelectric coolers	Maintain cell temperatures below 27°C during incubation
Passive	4 heat pipes	High conductance path from cell head ends to thermoelectric coolers

ment test cell during termination) to 5 °C (minimum allowable cell temperature during incubation), and are complicated by the small volume available for the experiment and the requirement that high and low temperature operations be carried on simultaneously (in different experiments). To satisfy these requirements in a Martian atmosphere (nominally 7 millibars CO_2), the thermal subsystem utilizes both active and passive elements. The active elements are thermoelectric coolers plus a large number of individually controlled heaters. The passive elements include heat pipes, thermal standoffs, convection/radiation shielding, surface coatings or tapes, and component placement.

The MSS and the ESS which make up the instrument are bolted to a Lander instrument mounting plate (IMP). Although the surrounding radiation/gaseous conduction environment was considered in the thermal subsystem design process, the IMP temperature variations, which are dependent on the Mars landing site, dominate the instrument thermal environment. The biology instrument had to be designed to operate with temperature variations of the IMP from 35 °C to −26 °C. The minimum environment assumes no heat dissipation internal to the instrument; the minimum Lander plate temperature will increase by approximately 0.5 °C for every watt dissipated internally by the instrument.

The ESS is tested to the extremes of the IMP temperature variation. Individual components in the ESS are mounted to appropriate heat sinks which have necessary thermal paths to the ESS housing. Installed in the Lander, the ESS housing is in intimate contact with the IMP which provides the primary heat sink.

The MSS consists of the three individual experiments, a common services module for helium supply and regulation, and nuclear detection systems for LR and PR experiment detection. The design objective is to thermally isolate each of these units from the other and, except for the nuclear detection system and the PR illumination assembly, from the Lander IMP. Within each module, subassemblies which must operate at high temperatures (>90 °C) are further isolated from the remainder of the module.

Table XIII summarizes the various elements making up the MSS thermal subsystem. The majority of thermal requirements are satisfied by the 43 individual heaters coupled with proper control of the conduction and radiation heat flow paths from the part to be controlled to surrounding hardware. Three different heater control schemes are employed: proportional control, electronic thermostat, and mechanical thermostat. The critical heaters are proportional control where, near the operating point, the heater power input is inversely proportional to the sensor temperature. The remainder utilize electronic or mechanical thermostat control, where the heater calls for full power when heating and none when off.

Some heaters are simply sequenced on and off during the mission and are sized to meet requirements for the total range of supplied voltage and environmental conditions. The four heat pipes and thermoelectric coolers (one each for GEx and LR and two for PR) are used to maintain cell head temperatures at or below 27 °C when the Lander IMP reaches a higher value. Each thermoelectric cooler, mounted to the IMP with four screws, is thermally coupled to one of the experiment head ends by a small ammonia heat pipe. When the control thermistor located in the GEx module heats to over 11 °C, the thermoelectric cooler is activated. The unit then cools one end of the heat pipe and provides a sink for heat rejection.

Other MSS thermal subsystem elements involve passive approaches to reducing heat losses with radiation/convection shields placed on the LR head end valve block, on the LR and PR detector assemblies, and on the GEx heated nutrient line between the valve block and the head end. The radiation/convection shield on the LR head end is shown in Fig. 34.

Maintenance of particular lines at required temperatures is accomplished in two ways. Many of the lines are provided with separate heaters (as shown on the far left in Fig. 34). These presented a problem of control over the total range of supplied voltage as well as the large number of complex shaped heaters. A second approach, primarily for maintaining nutrient lines at or above freezing, is the use of individual heaters mounted to the experiment cans. Nutrient lines are then thermally bonded to the cans (heated to approximately 10 °C) and remain comfortably above freezing even in the extreme environments expected. This concept is illustrated by

the gold tape-covered LR nutrient delivery line shown in Fig. 34. The can heater can be seen at the extreme left behind the heated line.

The can heaters provide another benefit in that they can be controlled to maintain the experiment cell and head end above minimum allowable incubation temperatures during the minimum part of the diurnal cycle.

The critical specific requirements satisfied by the thermal subsystem were

(1) Incubation—maintain test cells at $15\ ^{+12}_{-10}$ °C depending on experiment to be performed.

(2) Freezing protection—maintain water and nutrient reservoirs and lines above 0 °C.

(3) Sterilization—maintain specified test cells valve blocks and lines above selected sterilization temperature (typically 120° to 160 °C) for up to 3 h.

(4) Pyrolysis, elution, and termination—perform PR experiment detection modes which require test cell and organic vapor trap (OVT) temperatures as high as 725 °C.

(5) GCAA detector—maintain the GCAA detector at (32 ± 0.1)°C during gas analyses.

(6) Detector cleanup—elevate PR and LR detector temperatures above 90 °C to desorb trapped radioactivity.

Another important set of instrument requirements was to allow opening the experiment test cell seals only within specific temperature limits after they experience a high temperature operation, in order to prevent degradation of these critical seals.

IX. COMMAND CONTROL

The experiment activities of the biology instrument are controlled by digital commands sent from the guidance control and sequencing computer (GCSC) in the Lander. These commands operate the instrument either by accessing one of the three read only memories (ROM) or by directly initiating an instrument function (e.g., operating the SDA). When the ROM for an experiment is accessed it begins to step through a programmed series of events on a specific timeline. It will continue to execute events per its timeline until such time as it is either disabled, accessed at another address, or the power to the instrument is turned off. The bulk of the activities of an analysis sequence are caused by the automatic execution of these programmed ROM events.

During the course of an analysis sequence for the three experiments, several types of data such as temperatures and radioactivity counts are generated. As they accumulate, these data values are stored as digital words in the 128-word (16 bits per word) instrument memory. The contents of this memory are dumped to the Lander either by direct command from GCSC or when the memory signals the Lander that it is almost full and ready to be dumped. Additionally, the biology instrument generates four analog data points (three temperature and one pressure) which the Lander samples directly from the data acquisition and processing unit (DAPU).

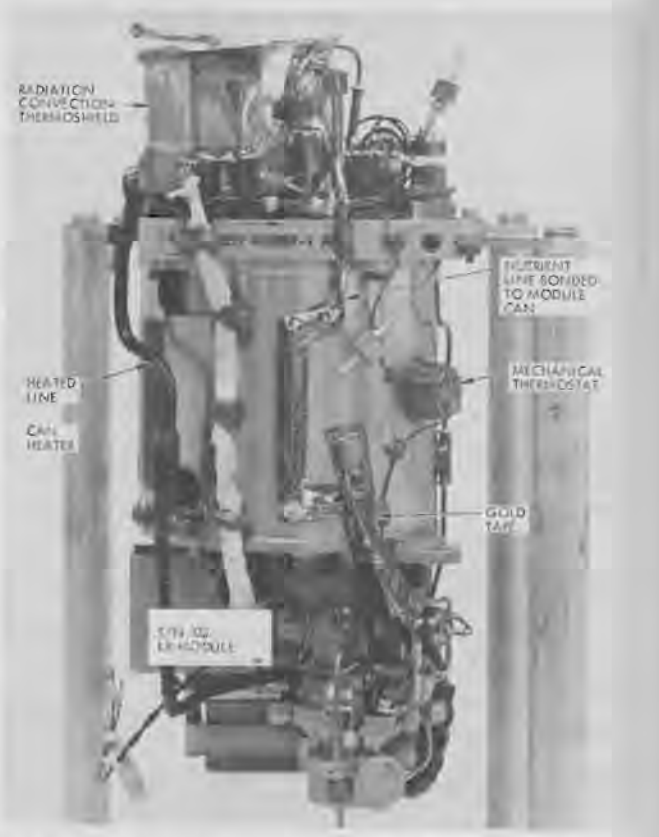

FIG. 34. Labeled release experiment module showing application of thermal control techniques.

A. GCSC control of the instrument

The commands with which the GCSC controls the biology instrument are stored in two tables, A and B, within the Lander GCSC. These tables contain the individual biology commands and for each the time to next command. When a biology sequence is to be run, the GCSC merely accesses one of the tables and reads the first command and the time to the next command. After sending the first command to the instrument it waits the correct time, gets the second command and sends it. In this way it follows through the steps of a command table for the particular sequence.

When Viking landed on Mars, the biology tables in the GCSC were loaded with a set of commands known as the initial computer load (ICL). ICL table A was set up to initialize the instrument on sol 3 by firing the thermal isolation valves, operating the motors, and regenerating the gas chromatograph columns. ICL table B contained a command set to accomplish the first set of biological analyses on soil from the surface. Of 312 commands in table B only about 200 were necessary to perform within the table so as to allow later reuse of large blocks of commands with only a minimum of uplink modification. This strategy allowed flexible operation of the biology instruments without making the uplink command requirements prohibitively large.

B. Instrument sequencing

To produce the command tables which operate the biology instrument, a detailed knowledge is required of how the instrument will respond to a given command sequence and the constraints which pertain to operation of the instrument. To aid in creation of these sequences, a computer program is used which accurately models the response of the biology instrument to any series of commands that are sent to it. It prints out a complete listing of all experiment events and the time at which they occur for any command sequence. Additionally, the program recognizes almost all of the constraints on the operation of the instrument and will either reschedule experiment activities to avoid constraint violations or will at least alert the user to the existence of a violation.

There are several categories of sequencing constraints on the instrument. One major category is the thermal constraints. Because of the large diurnal temperature variations expected on the Martian surface and the desire to maintain soil samples at fairly constant temperatures, it is necessary to schedule certain events such as high wattage heating or nutrient injections to occur at specific times in the diurnal temperature cycle. A second category of constraints consists of those which forbid some activities in one experiment during critical activities in another experiment. This category of interexperiment conflicts also includes constraints on simultaneous use of the vent systems and the helium supplies.

In addition to the thermal and interexperiment constraints on the operation of the instrument, there is a large assortment of other operational constraints including possible conflicts with certain Lander activities.

During mission operations the creation of an operational sequence for the biology instrument proceeded as follows. First, the biology science team decided which major experiment activities were to occur in this sequence. A closely similar sequence was then selected from a previously established dictionary of experiment sequences. This was modified to include all of the activities desired by the science team and was processed through the biology sequencing computer program to check for constraining violations. This process was iterated with modifications to the sequence until all constraint violations had been resolved. The sequence was then sent to the overall Lander sequencing computer program where it was checked against the Lander constraints. Once again, an iterative process with sequence modifications was necessary. When all conflicts had been resolved the command file for the sequence was merged into the Lander uplink file and sent to the Deep Space Network (DSN) for transmission to the Lander.

C. Computer reduction of down-linked data

When the Lander receives the data generated by the biology instrument, it stores it until a transmission window is available for down linking. This may be either by direct transmission to earth or via a relay through the orbiter. The biology data is mixed in with all other Lander data during transmission. After data are received by the DSN they are sent to JPL where a computer program separates them according to experiment and makes them available to data reduction programs of the individual experiments.

There are two computer programs for processing data from the biology experiments. The first of these receives the data in the form of the raw dumped memory frames and, using inputs from the sequence generation program, time-tags the data and separates them according to type (e.g., PR ^{14}C count). The time tag process is complicated by the absence of any time identification of the data words as they are stored by the instrument. It is accomplished using a precise prediction of the down-link data generated by the command up-link program to match the received data to that which was predicted. It also decalibrates the data into scientific units and checks for out of range values. It gives the science team its first quick look at the data as they are returned from Mars.

The first biology data reduction program also creates a working data file for the second program. This is a file of time-tagged and decalibrated data values which is added to daily as the mission proceeds. The second of the biology data reduction programs is interactive and is designed to be used by members of the science team to perform higher order processing of their data. It accesses the data in the working data files and performs statistical analyses, curve fitting, and plotting functions as requested from the computer terminal. The science team is able to use this program to analyze in detail the results of their experiments.

X. Operations

On July 20, 1976, Viking Lander I settled gently on the plains of Chryse and commenced operations. For the next 300 Martian sols, the biology instrument successfully conducted 13 separate experiments on 4 different soil samples. The primary mission was successfully completed before superior solar conjunction when commanding of the Lander science investigations was interrupted for several weeks. After conjunction secondary experiments were conducted until May 1977 when the helium consumable gas used to engage the test cell carousels and move liquids and gases into and out of the experiments was depleted, as expected. The only degradation in instrument operation occurred in the secondary experiments during the gas exchange experiment third soil analysis cycle when the gas chromatograms (Table X) detected no gases due to a presumed leak in the test cell. During the Lander I biology instrument operation 52 gas chromatograms were taken for the GEx experiment, 6 pyrolytic release experiments were completed, and 9 radioactive nutrient injections were made in four different tests for the LR experiment.

On September 3, 1976 Viking Lander II arrived at

Utopia plains of Mars approximately 180° around Mars from Lander I, and at a much more northerly latitude. The biology instrument's primary mission was also completed by conjunction and the secondary experiments were terminated by depletion of the helium reservoir on the expected date. The only malfunction occurred during the secondary mission when a leaking valve in the PR experiment prevented collection and measurement of the carbon-14 during the 4th and 5th soil sequences. During the Lander II biology instrument operation, 13 separate experiments on 4 different soil samples were processed, 57 gas chromatograms were taken for the GEx experiment, 3 pyrolytic release experiments were successfully completed, and 9 radioactive nutrient injections were made in five different tests for the labeled release experiment. A total of about 2900 commands were processed by the biology instrument on each Lander during the complete mission.

The scientific results of these experiments are being published separately by members of the biology science team.[16–19]

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[1] G. A. Soffen and A. T. Young, Icarus **16**, 1 (1972).
[2] R. S. Young, Space Life Sci. **4**, 505 (1973).
[3] C. Sagan, Sky Telesc. **50**, 15 (1975).
[4] J. S. Martin and A. T. Young, Astronaut. Aeronaut. **14**, 22 (Nov. 1976).
[5] J. S. Hubbard, G. L. Hobby, N. H. Horowitz, P. J. Geiger, and F. A. Morelli, Appl. Microbiol. **9**, 32 (1970).
[6] N. Horowitz, J. S. Hubbard, and G. L. Hobby, Icarus **16**, 147 (1972).
[7] G. V. Levin, Icarus **16**, 153 (1972).
[8] G. V. Levin, D. G. Shaheen, W. A. Lindgren, and E. Rich, Presented at Intern. Congr. Microbiol., Mexico City (August 1970).
[9] G. V. Levin and P. A. Straat, Origins Life **7**, 293 (1976).
[10] V. I. Oyama, Icarus **16**, 167 (1972).
[11] V. I. Oyama, G. C. Carle, B. J. Berdahl and E. J. Merek, in *Planning Challenges of '70's in Space and the Public Domain*, edited by G. W. Morgentholer, G. Chacks, and R. G. Morra (American Astronomical Society, Denver, 1970), Vol. 26.
[12] W. Vishniac, Aerosp. Med. **31**, 678 (1960).
[13] G. V. Levin, A. H. Heim, J. R. Clendenning, and M. F. Thompson, Science **138**, 114 (1962).
[14] *Biology and the Exploration of Mars*, edited by C. W. Bruch, in C. S. Pittendrigh, W. Vishniac, and J. P. T. Peterman, Publ. No. 1296 (National Academy of Sciences, National Research Council, Washington, D.C., 1966), p. 487.
[15] R. S. Young, *Exobiology, The Search for Extraterrestrial Life*, edited by M. M. Freundlich and B. M. Wagner (AAS Publications Office, Tarzana, 1969), p. 29.
[16] H. P. Klein, N. H. Horowitz, G. V. Levin, V. I. Oyama, J. Lederberg, A. Rich, J. S. Hubbard, G. L. Hobby, P. A. Straat, B. J. Berdahl, G. C. Carle, F. S. Brown, and R. D. Johnson, Science **194**, 99 (1976).
[17] V. I. Oyama, B. J. Berdahl, and G. C. Carle, Nature **265**, 110 (1977).
[18] N. H. Horowitz, G. L. Hobby, and J. S. Hubbard, Science **194**, 1321 (1976).
[19] G. V. Levin and P. A. Straat, Science **194**, 1322 (1976).
[20] J. S. Hubbard, J. P. Hardy, and N. H. Horowitz, Proc. Nat. Acad. Sci. (Wash.) **68**, 574 (1971).
[21] J. S. Hubbard, J. P. Hardy, G. E. Voecks, and E. E. Golub, J. Mol. Evol. **2**, 149 (1973).
[22] G. C. Carle, J. Chromatogr. Sci. **8**, 550 (1970).
[23] D. M. Anderson, K. Biemann, L. O. Orgel, J. Oro, T. Owen, G. P. Schulman, P. Toulmin III, and H. C. Urey, Icarus **16**, 111 (1972).
[24] S. L. Hess, R. M. Henry, C. B. Leovy, J. A. Ryan, J. E. Tillman, T. E. Chamberlain, H. L. Cole, R. G. Dutton, G. C. Greene, W. E. Simon, and J. L. Mitchess, Science **193**, 788 (1976).
[25] S. L. Hess, R. M. Henry, C. B. Loevy, J. A. Ryan, J. E. Tillman, T. E. Chamberlain, H. L. Cole, R. C. Dutton, G. C. Greene, W. E. Simon, and J. L. Mitchell, Science **194**, 78 (1976).
[26] D. W. McMorris, Anal. Chem. **46**, 42 (1974).

Precision absolute measurements of strong and highly inhomogeneous magnetic fields[a)]

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The low-temperature ($\lesssim 4$ K) dependence of the photoconductance in n-type silicon on the conduction electron and bound donor electron spin state serves as the basis of a high-precision, wide-range magnetic field measuring probe, which by virtue of its very small dimensions is well suited for spatial mapping of highly inhomogeneous fields produced by superconducting magnets. The probe may also be adapted to power and frequency measurement of microwave sources operating at ~mW power levels and frequencies up to ~500 GHz.

Among the many methods for measuring magnetic fields, only the resonance ones provide absolute field measurements to a precision of better than 1 part in 10^5 with a simple laboratory instrument. Rotating coils, Hall-effect probes, and magnetoresistance probes each have their respective merits and disadvantages, but dimensions of at least a few mm are required, and precision of about 1 part in 10^4 is about as high as can be expected. The resonance methods, based on accurate frequency standards and known magnetogyric ratios of nuclei or electrons, offer high precision but require relatively large samples when the resonances are detected by standard means such as monitoring the reactive electromagnetic radiation field. In addition, these conventional radio-frequency and microwave resonance methods are frequently narrow band, requiring tuned coils or cavities for high sensitivity measurements. We describe here a method of carrying out resonance measurements which retains all the advantages of the standard resonance method, but is also broadband and applicable even for very small sample volumes. This is achieved by detecting the resonance at liquid helium temperatures, where the noise level is very low, and through a property of the system for which the signal-to-noise ratio decreases more slowly than linearly with decreasing sample volume, in contradistinction to the standard detection technique in which the reactive electromagnetic field is monitored.

The method is based on spin-dependent photoconductivity in semiconductors, the physics of which has been described in several publications.[1-3] Most of the work has been on n-type silicon, and for simplicity of presentation we confine ourselves to that material in this report. At liquid helium temperatures (≤ 4.2 K), the dark current for uncompensated silicon containing group V donors at concentrations below $10^{17}/\text{cm}^3$ is negligible in relation to the photocurrents which will be employed. In the presence of extrinsic radiation ($0.05 < h\nu < 1.18$ eV) or intrinsic radiation ($h\nu > 1.18$ eV), where $h\nu$ is the photon energy, the photoconductance is proportional to the product of carrier generation rate ($\propto$ radiation intensity), carrier mobility, and carrier lifetime. The latter two quantities vary with mode of illumination (extrinsic or intrinsic) because of the different charge states[4] of the impurities resulting from the two types of illumination. Since the technique we are about to describe operates most effectively at impurity concentrations and temperatures where the lifetime of photoexcited carriers is the dominant parameter for determining photoconductance, we confine the description of operation to that case, losing little generality by neglecting changes in mobility.[3] Thus, under constant radiation intensity (and assumed constant mobility), the photoconductance is proportional to the carrier lifetime. For a silicon sample doped with group V donors to a concentration of, for example, $3 \times 10^{16}/\text{cm}^3$, and held to a group III acceptor concentration of, or below, $10^{13}/\text{cm}^3$, a readily obtained condition, the dominant conduction-electron lifetime limiting mechanism at low temperatures is capture by neutral donors,[3] denoted by the reaction

$$D^0 + e^- \rightarrow D^-. \tag{1}$$

This reaction, however, occurs only when the neutral donor, D^0, and a conduction electron interact in a singlet spin state,[2,3] since the resultant D^- state is stable (bound) only in the electronic singlet spin state, and the probability of spin flip during capture is very small. If the neutral donors are highly spin-polarized, the conduction electrons also are highly spin-polarized, since for the impurity concentrations employed, the rate of spin exchange[6] between donors and conduction electrons exceeds the rate of electron capture or generation. Thus, for donors in a highly spin-polarized state ($\mathcal{P} \simeq 1$), the neutral donors and conduction electrons are expected to collide mostly in a triplet spin state, leading to long carrier lifetimes and a high photoconductance, whereas in an unpolarized ($\mathcal{P} \sim 0$) state, where singlet state collisions of conduction electrons and donors are abundant, the photoconductance is reduced because the carrier lifetime

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