

Phoenix Mars Mission—The Thermal Evolved Gas Analyzer

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The Phoenix spacecraft that was launched to Mars in August 2007 landed safely on the Martian northern arctic region on May 25, 2008. It carried six experiments to study the history of water on the planet and search for organic molecules in the icy subsurface Martian soil. The spacecraft is a lander with an arm and scoop designed to dig a trench through the top soil to reach an expected ice layer near the surface. One of the instruments on board is the thermal evolved gas analyzer (TEGA), which consists of two components, a set of eight very small ovens that will heat samples of the ice soil mixtures from the trench to release imbedded gases and mineral decomposition products, and a mass spectrometer that serves as the analysis tool for the evolved gases, and also for measurements of the composition and isotopic ratios of the gases that comprise the atmosphere of Mars. The mass spectrometer is a miniature magnetic sector instrument controlled by microprocessor-driven power supplies. One feature is the gas enrichment cell that will increase the partial pressures of the noble gases in an atmosphere sample by removing all the active gases, carbon dioxide, and nitrogen, to improve the accuracy of their isotopic ratio measurements. (J Am Soc Mass Spectrom 2008, 19, 1377–1383) © 2008 American Society for Mass Spectrometry

The Phoenix Mars Mission is the first of the NASA Scout programs. These are low cost missions to Mars that are led by a single principal investigator. The goal of the Phoenix mission is to study the history of water and search for organic molecules in the subsurface icy soils of Mars. Data from the Mars Odyssey Orbiter spacecraft neutron monitor showed large amounts of subsurface water-ice in the northern arctic plains. Hence, the Phoenix spacecraft was targeted to land on this plane. It touched down safely at 68° north latitude on May 25, 2008, after a 9-month voyage.

The instrument compliment of the Phoenix lander consists of six instruments: a descent camera, a panoramic camera, a robotic arm with a scoop at its far end and a camera attached there, a meteorology suite of instruments, the microscopy electrochemistry and conductivity analyzer (MECA), and the thermal evolved gas analyzer (TEGA).

The robotic arm, 2 m long, will dig a trench through the top soil to the icy layer suspected to exist just below the surface. Samples from the trench will be collected for analysis by MECA and TEGA. The former will determine chemical and physical properties of the soils and ices while TEGA, which consists of a set of eight tiny, single use ovens, will first melt any ice in the samples to evolve gases from them, and then thermally decompose the soils to determine their mineralogy. A

mass spectrometer will perform the analysis of the evolved gases. Results from these instruments will aid in developing an understanding of the history of the Martian arctic.

The Martian environment is quite hostile to the operation of scientific instruments on its surface. Temperatures range from near 0 to -100 °C. The surface pressure is about 10 mbar, which is a problem for high voltage power supplies. This will be addressed later. Dust storms can develop at a moment's notice. Power, coming from the sun via solar panels, is limited, as are data storage and the data transmission rate to earth. Data cannot be transmitted directly from the Martian surface to earth due to limitations on the available power and size of the antenna on the lander. Therefore, data must be relayed to earth via one of two orbiting satellites, the Mars Odyssey and Mars Reconnaissance Orbiter. So, data are received on earth in batches, usually twice per day. The one-way transmission time is over 15 min, which prevents real time control of the instruments. Blocks of commands that include modes of operation of the instruments and parameter settings are transmitted to the lander once per day. The instruments then perform the specified operations and store the data for transmission to earth via one of the orbiting spacecraft. This process is repeated each day from a predetermined plan that is continuously updated as more is learned about Mars. Each instrument may not be operated every day due to limitations of the resources. This is clearly a harsh environment for a mass spectrometer or any other sensitive scientific instrument.

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The thermal evolved gas analyzer (TEGA) consists of two main components: the thermal analyzer (TA) designed and constructed by the University of Arizona Lunar and Planetary Laboratory, and the evolved-gas analyzer or EGA, a mass spectrometer, designed and constructed by the University of Texas at Dallas Physics Department.

The TA is a calorimeter with a set of eight small ovens patterned after a similar instrument that was prepared for an earlier mission. Each oven will accept a soil sample delivered by the robotic arm. The sample will be sealed in the oven and heated slowly to first melt any ice in the sample, then heated to 1000 °C. The energy input to the oven is carefully monitored to detect solid-liquid-gas-phase transitions and the decomposition of minerals in the soils. Many minerals will decompose at temperatures less than 1000 °C releasing telltale gases. The evolved gases from the melting ice and the mineral decomposition are swept to the mass spectrometer by a carrier gas of high-purity nitrogen. From the composition of the evolved gases and the temperatures at which they are released, as well as the energy involved in the decomposition, identification of the minerals is possible.

The EGA is a magnetic-sector-type mass spectrometer. The mass spectrometer will identify volatiles from the samples as they are heated and will determine their relative abundances and the isotopic ratios of the principal elements. Between experiments with the TA ovens, the mass spectrometer will sample the atmospheric gases and determine the bulk composition and the isotopic ratios of carbon, oxygen, nitrogen, hydrogen, and the noble gases. It will also measure the water vapor content of the atmosphere over the 90 sols operation on the surface.

Several features of a magnetic sector instrument cause it to be particularly suitable for Mars exploration and to serve as a detector for TEGA. These are (1) simplicity of design, (2) stability, (3) ruggedness, (4) very good mass resolution and the ability to separate small amplitude peaks from adjacent very large amplitude peaks, and (5) minimal electromagnetic interference with other instruments and systems. The instrument has a considerable flight heritage: Apollo 17 ALSEP [1], Pioneer Venus Sounder Probe [2], ISIS-II [3], Atmospheric Explorers C, D, and E [4], Giotto NMS [5], as well as numerous sounding rockets.

Major components of the mass spectrometer are (1) a gas handling manifold containing a gas transfer tube from the TA ovens to the mass spectrometer ion source, the TA gas inlet valve and microleak, an atmospheric gas inlet valve and microleak, and a gas enrichment cell (GEC) for improving the sensitivity to minor noble gas species; (2) the mass spectrometer that consists of an ion source, a magnetic mass analyzer, four electron multiplier detectors, and associated electronics circuits; and (3) a small sputter-ion pump to maintain a good vacuum in the analyzer.

Gas Handling Manifold

The two inlet paths through the gas manifold admit gases into the ion source of the instrument. These are (1) a direct path through the transfer tube from the furnace, and (2), a direct path from the atmosphere through a short transfer tube. Figure 1 is a drawing of the gas flow paths through the instrument. The atmosphere transfer tube feeds gas into the GEC container and to the atmosphere inlet valve on the ion source. An inline valve controls the amount of gas that can be admitted to

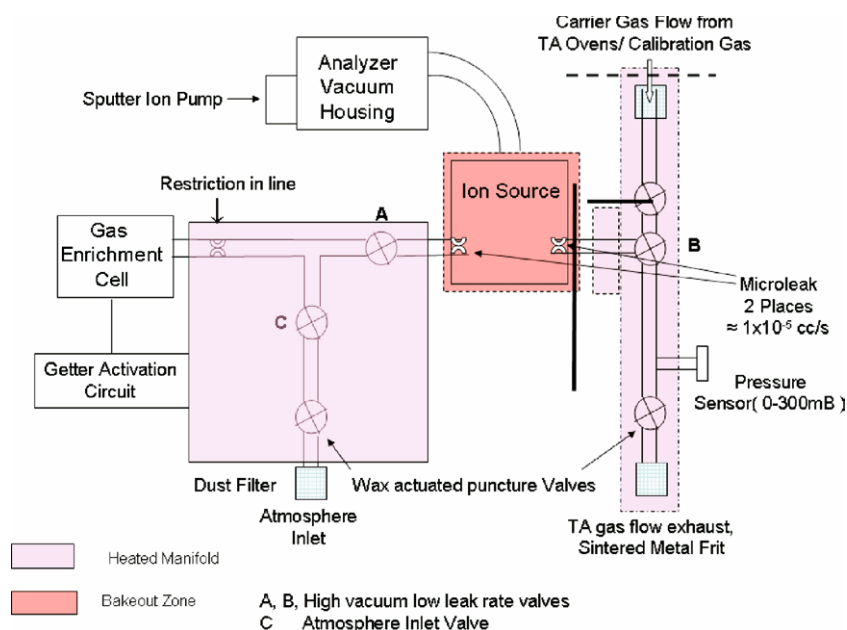


Figure 1. Drawing of the mass analyzer and associated gas manifold.

the GEC. The entire manifold and transfer tubes are heated to 35 °C to keep water vapor and other volatiles from freezing onto the walls.

The microleaks that control the rate of gas flows into the mass spectrometer ion source consist of a bundle of capillary glass tubes that are drawn out to reduce their diameters to the order of a fraction of a micron so that the conductance of the bundle is about 1×10^{-5} cc/s. for the TA inlet and somewhat larger for the atmosphere inlet. The nitrogen carrier gas pressure from the TA ovens is maintained above the Mars atmosphere pressure by a frit pressed into the exhaust tube to minimize back flowing of atmospheric gases up the exhaust tube, which could mix with the sample gases being transported from the ovens. Gases admitted to the ion source flow out of it through the ion object slit of the ion source and into the mass analyzer vacuum chamber. The conductance of the object slit is 5 cc/s. A sputter ion pump, to be described later, exhausts the gases from the vacuum chamber. The pumping speed of the ion pump is about 1 L per s, which is sufficient to maintain a pressure in the analyzer chamber of less than 1×10^{-7} mbar. These flow rates result in an ion source pressure of 8×10^{-6} mbar and since the analyzer is below 1×10^{-7} mbar, there is very little back flow of gases from the analyzer chamber into the ion source. Therefore, any mass discrimination due to various pumping speeds of the different gases will have a very minimal effect of the accuracy of measurement.

To improve sensitivity for lower abundance noble gases, the gas enrichment cell (GEC) is used to purge a sample of the atmosphere drawn into its volume through the atmosphere inlet. A non-evaporable getter (SAES ST172) heated to about 250 °C scavenges essentially all the CO₂ and nitrogen leaving argon (partial pressure ~2%) as the dominant gas in the sample. Removing the CO₂ and N₂ increases the partial pressures of all the other gases by a factor of at least 50, which improves the sensitivity of their measurements by the same factor. Tests with the getter have shown that greater than 99% of both the carbon dioxide and nitrogen are removed from a test gas mixture having the ratios of the Martian atmosphere, ~3% N₂ and ~2% argon with the balance being CO₂. Over 2 mbar/L of atmospheric gases are adsorbed by the getter leaving about 50 mbar/cc, all noble gases, for analysis. This concentrated sample is then admitted to the ion source through the same leak as the directly admitted atmosphere sample. Tests have also shown that the getter does not get or fractionate methane and hence will concentrate it by the same factor. This feature will aid in the possible detection of methane in the atmosphere.

Mass Spectrometer

The mass spectrometer ion source consists of a small chamber (1 cm³) through which an electron beam passes that ionizes a fraction of the gas molecules. The electron beam is produced by thermal emission from

one of two small tungsten filaments; the second filament is a backup. The filament and associated electronics each require 1 W of power. The thermally emitted electron beam is controlled by a microprocessor to produce two emission currents (25 and 200 μA) and four electron energies (90, 37, 27, and 23 eV). These features extend the dynamic range by a factor of 8 at the higher emission current and provide information on the molecular constituents by varying their cracking patterns and charge states using the lower electron energies. For example, CO₂ spectrum has very high mass peaks (besides the parent peak at 44 Da) at 28 Da (CO), 22 Da (doubly charged CO₂), 16 Da (O), and 12 Da (C). Using 37 eV electrons, the 22 Da peak disappears and the others are greatly reduced. At 27 eV, all dissociated peaks except CO are below 1% of the parent. The downside to using the lower electron energies is the loss of sensitivity with decreasing energy. This extended dynamic range and additional information on molecular constituents will facilitate and greatly simplify analysis of the mass spectrum data.

Ions produced in the source are drawn out by a high voltage and collimated into a beam by a series of slits, the smallest being the object slit, the image of which is focused by a magnetic field onto a set of collector slits. Ion trajectories in the magnetic field are arcs, the radii of which are a function of their m/z ratio. Four specific trajectories are selected to cover the mass ranges, 0.7–4, 7–35, 14–70, and 28–140 Da. Using four channels reduces the magnitude of the mass scan and provides simultaneous coverage of the mass ranges. The width of the object and collector slits and the radius of the ion path in the magnetic field determine the mass resolution of the instrument. This is set at 140 (M/ΔM) for the high mass channel. The mass resolution of the other channels is proportionally reduced.

The chosen ion beam paths exit the magnet through collector slits into ceramic electron multiplier (CEM) detectors that operate in the pulse counting mode. Each channel has a pre-amp/discriminator to shape the CEM output pulses and a counter. The background counting rate with no emission current is zero counts per second. The minimum detectable signal is one count per ion accumulation period. This period can be set by command, but is typically 50 to 200 ms. Since the signal is digital, the precision is based on the statistical error of the count number and is immune to the detector system inherent noise. Data in the form of pulse counts from the electron multipliers during each voltage step of the ion source are sent to the data processing unit for further processing and formatting for telemetry transmission.

The instrument sensitivity is adjusted so that the maximum counting rate at an ion source pressure of 8×10^{-6} mbar is 2 MHz. The frequency of the preamp is 12 MHz. At this rate, the probability of missing a count at the maximum frequency is <4%. The dynamic range is then at 1 count/s equal to 2×10^6 ; using the high sensitivity adds a factor of eight, for a dynamic range of 1.6×10^7 . Adding the counting rates for 100 measure-

ments at each mass should allow measurement of a constituent at the 100 ppb mixing ratio (partial pressure of 1×10^{-12} mbar) to a statistical precision of 10%; at 10 ppb (partial pressure of 1×10^{-13} mbar) the precision is 30%. The realized sensitivity will depend on the residual peak amplitude at the particular m/z of interest.

The magnetic analyzer consists of a permanent magnet having a field strength of 6500 gauss (0.65T) in its gap. The most efficient magnet material with regards to volume, and hence weight, is NeBFe. This material is available with an energy product of 48 MGOe and, as a result, the magnet mass is only 500 g. However, NeBFe also has a very high-temperature coefficient ($-0.15\%/^{\circ}\text{C}$) and thus the field strength varies significantly with temperature. With a field strength change, the trajectory of a given mass for a given ion acceleration voltage is displaced. An algorithm was developed to generate a temperature compensation that modifies the ion acceleration voltage to bring the trajectory for a given mass ion back to the original position. This is important for the peak hopping mode of operation to be described later.

Figure 2 is a photograph showing the mass analyzer before the cover was welded on. The four electron multipliers are mounted just after their respective collector slits; the ion source is to the right side; the magnet is at the top. The ion pump is to the bottom with a getter appendage attached to it.

The analyzer section is pumped by a small ion pump. Its configuration is that of a typical diode ion pump having an anode mounted on ceramic standoffs between two cathodes plates, one made of tantalum and the other of titanium. The entire assembly is housed in an appendage to the mass analyzer vacuum chamber and is placed between the poles of a magnet with a field strength of 3 kG. The passage way from the pump cavity to the vacuum housing is carefully baffled to prevent any ions or electrons from escaping the ion pump and causing background counts in the electron multipliers. As a backup to the ion pump in case the

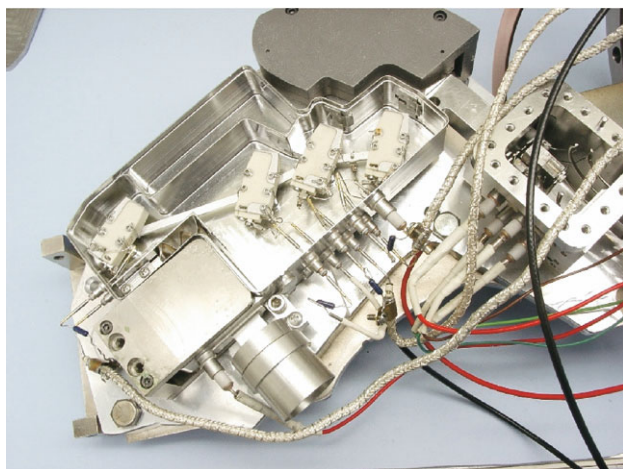


Figure 2. Mass analyzer.

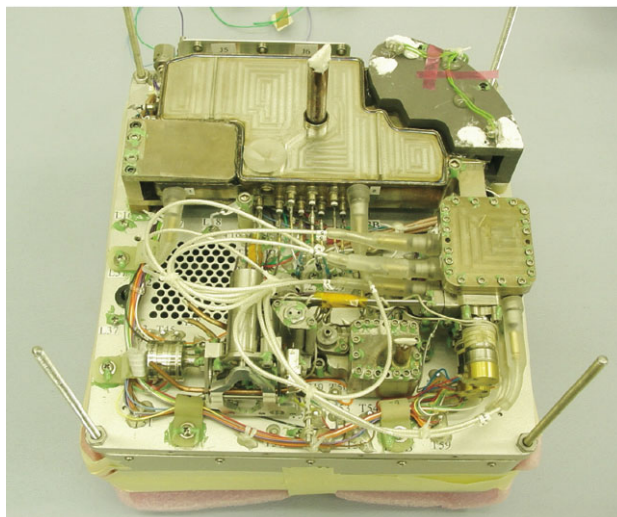


Figure 3. Complete mass spectrometer package.

pressure in the analyzer vacuum chamber should rise above that at which the ion pump will start, a non-evaporable getter, same as in the GEC, is mounted in a small appendage to the analyzer housing. This getter can be activated by command to pump the chamber down.

Figure 3 shows the complete mass spectrometer package with the cover removed. The mass analyzer is at the top, with the ion source at the right. The high vacuum valves protrude downward from the ion source housing. The gas manifold lies across the bottom.

Electronics

The electronics subsystem consists of three modules that are mated together on top of the instrument support plate as shown in Figure 4 (the electronics power supply units were designed and constructed by Battel Engineering, Scottsdale, AZ). The top, middle, and bottom modules are the processor module, low voltage module, and high voltage module, respectively. The



Figure 4. Picture of the electronics assembly.

electronics are functionally similar to those of previously flown mass spectrometers, providing all of the operational voltages and currents for the mass analyzer, ion pump, and GEC, plus providing data collection, formatting, data storage, and status/housekeeping information required to satisfy the measurement objectives.

The processor module consists of a dedicated 80C196KD microprocessor, FPGA, memory, bus drivers, and associated circuitry required to control and monitor the instrument functions as well as to store accumulated data. The module also contains a preamp card consisting of four Amptek A121 hybrid charge sensitive preamplifier-discriminators (Amptek, Inc., Bedford, MA) designed for fast pulse counting. This card accepts the electron pulses from the electron multipliers and shapes them for storage in pulse counters in the processor section of the module.

The low voltage module converts primary power (21 to 35 V) from the Phoenix Lander to the numerous voltages required by the instrument. The module provides nine isolated outputs including power for the processor module, power for low-noise analog functions, switched power for the high voltage ion pump and CEM functions, and AC drive for the various floating high voltage functions. Dual high-powered switched getter functions and a power-on reset functions are also provided by this module.

The high voltage module provides all of the high voltages that interface to the analyzer. These include the precision ion accelerating voltage (200 to 2000 V) stepping power supply needed by the mass spectrometer to accelerate the ions before entering the magnetic analyzer portion of the spectrometer. A 16 bit D/A converter controls the power supply output voltage. For standard stepping, the precision of the output voltage is better than 14 bits after the 5 ms settling interval.

In addition to the sweep system, the high voltage module includes the filament emission circuitry plus CEM high voltage and ion pump high voltage supplies. The emission and bias control functions float at the accelerating potential. Two emission levels as well as four different electron energies can be obtained by commands from the computer. Power for the two filaments is provided using AC drive to achieve high efficiency. Precision emission control is achieved by modulating the AC drive using magnetic amplifiers in series with each filament.

Separate oscillators and high voltage multipliers provide the CEM high voltage and ion pump power. The CEM power supply is controllable from -1000 to -3500 V. The ion pump power supply has an unloaded output of 3000 V.

For an instrument that is to operate on the surface of Mars, all high voltages must employ special electrostatic shields to prevent corona discharges in the 8 to 10 mb atmospheric pressure environment. The high voltage module uses a carefully constructed Faraday shield to prevent high voltage breakdown. Shielded encapsulation methods are used for the majority of the high voltage

functions. However, the emission control section uses a special shielded enclosure without encapsulation.

High voltage connections from the high voltage module to the analyzer must also be shielded. This is accomplished using special vacuum feedthru with shielded cables and boots that seal each connector to its respective vacuum feedthru. The boots fit tightly over the feedthrus in the mass analyzer housing.

Computer System Software

The EGA system software, written for the EGA computer, controls and monitors the instrumentation and stores the mass spectrometer data for transmission back to Earth. To that end, software development incorporates a process that is geared toward reliable and robust code. Basic functions of the system software include (1) receiving and transmitting data via the RS-422 to the external computer; (2) parsing and executing commands directed to the computer; (3) providing autonomous and semiautonomous control of the mass spectrometer; and (4) monitoring the status of all instrument parameters and experiment sequencing.

Operation of the Instrument

Two operating modes are available. One consists of sweeping in a stepwise manner the ion acceleration voltage to cover the entire mass range over the four channels to determine what gasses are present in the furnace sample or in the atmosphere, and the relative abundances of each constituent. This mode is good for a broad brush look at the composition of the gas sample but is not very efficient in the utilization of time because too much time is spent moving between peaks where there are no data of interest. The other mode, called the peak hopping mode, or hops mode, involves adjusting the ion accelerating voltage to hop from peak top to peak top. On a given peak, usually seven measurements of counting rate are made while stepping over the top of the peak. A step size as small as 0.01 to 0.02 Da is used. The amplitude of the peak is determined by fitting a curve to the seven data points.

Figure 5a is a typical mass peak at 44 Da taken via the sweep mode. The jagged line is a plot of the counting rate versus sweep voltage, which in this plot has been converted to m/z . The solid smooth curve is a plot of a mathematical expression of a peak shape curve to be fitted to the data peak shape. Figure 5b shows how the seven data points are located relative to the curve to be fitted. In data reduction, a least-squares fit of the height of the data peak top points to the peak-shape function is performed.

The dwell time for the accumulation of counts is adjustable by command and will be selected as a function of the expected counting rate for each mass peak to be measured. Those peaks having high counting rates will have a shorter accumulation time. There is a dead time imposed between each accumulation period as the high voltage sweep power supply is commanded to a new

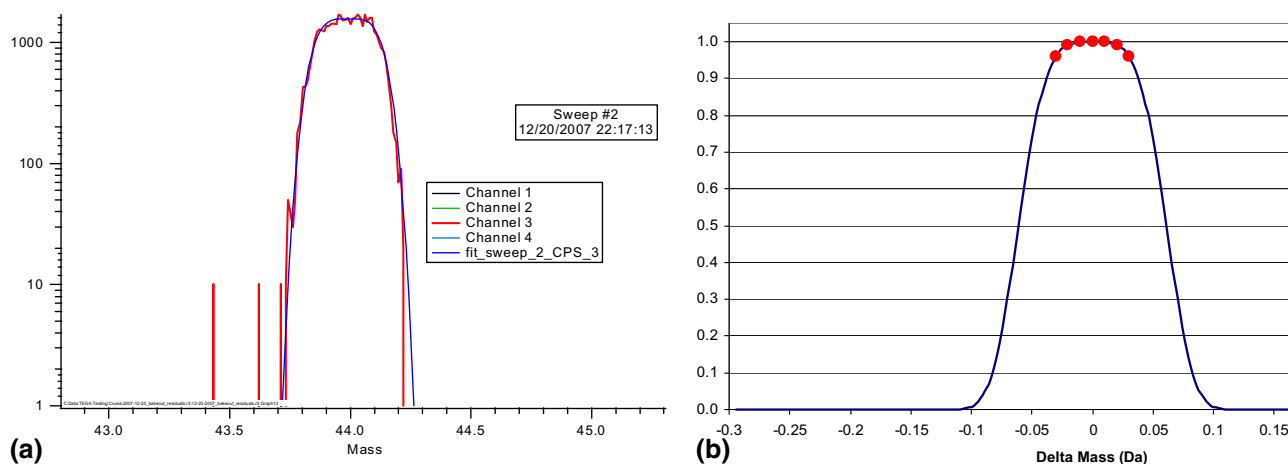


Figure 5. (a) Typical mass peak with peak shape curve. (b) Seven data points to which shape curve is fitted.

voltage. The settle time of the power supply is a function of the voltage step size and ranges from 5 to 50 ms.

The hops mode described above is used to measure isotopic ratios of the various elements and can also be used to monitor a given mass peak to determine the exact temperature at which the molecule is released from the sample in the TA. For example, the temperatures at which water vapor and carbon dioxide are released can be measured as the sample is heated.

Performance Characteristics

Figure 6 is a typical mass spectrum in the sweep mode of residual gasses in the mass spectrometer. The four

channels are shown from 1, lowest mass range, to 4, highest mass range. Mass ranges of the four channels are: Channel 1, 0.7–4 Da, Channel 2, 7–35 Da, Channel 3, 14–70 Da, and Channel 4, 28–140 Da. The ordinate scale is in counts per accumulation period, 200 ms.

Expected evolved gasses are H₂O, CO₂, H₂, and O₂, plus possibly SO₂ and some hydrocarbons. The isotopic ratios of carbon, oxygen, and hydrogen are determined in the analysis of the data. ¹³C/¹²C is found from the 45/44 Da ratio from CO₂. ¹⁷O will produce a small factor of uncertainty at 45 Da, but, assuming a correction for ¹⁷O based on the earth ratio, will introduce a very small error in the carbon isotopic ratio. ¹⁸O/¹⁶O

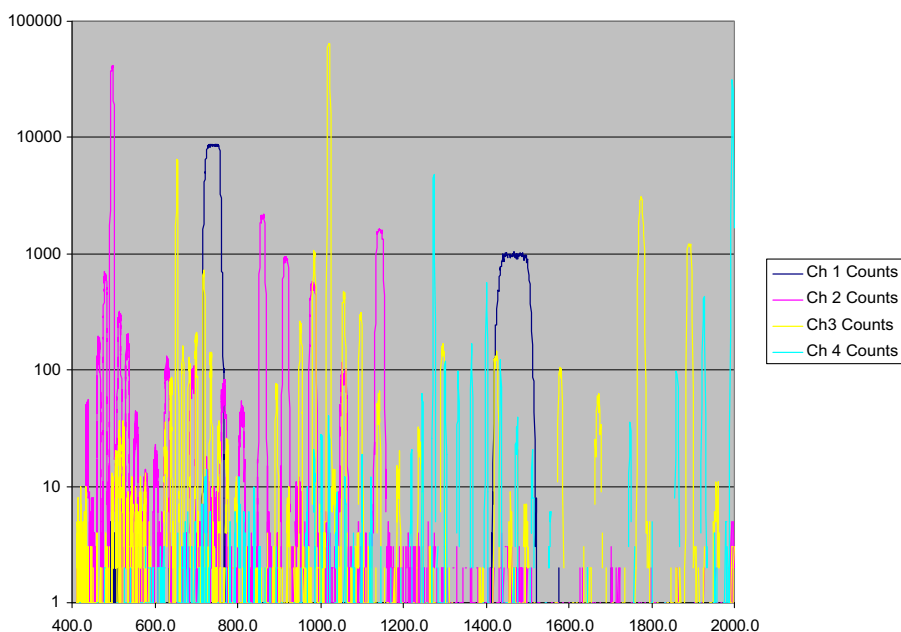


Figure 6. Mass spectra of residual gasses in mass analyzer. X-axis is sweep voltage; Mass number (m/z) increases from right to left. Y-axis is counting rate for each ion species. Channel 1 mass 1 is at 1400 to 1500 V; mass 2 is at 750 V. Channel 2 mass 12 is at 1150 V; mass 16 is a 860 V. Channel 3 mass 15 is at 1900 V; mass 28 is at 1000 Vs. Channel 4 mass 28 is at right edge; mass 44 is at 1250 V.

from CO₂ is derived from 46/44 Da and D/H is obtained from the 3/2 Da positions in the spectrum and verified at the 19/18 positions. Fluorine, if any, could be an uncertainty at 19 Da.

The key parameters of the mass spectrometer are given in Table 1.

Packaging of Instrument

Figure 7 is a picture of the instrument package. The package is divided by a mounting plate. The lower section houses the electronics modules; the upper section contains the mass spectrometer that is fastened to the mounting plate. The silver colored covers are extruded aluminum. Size and mass are given in Table 1.

Mission Parameters

Launch of the Phoenix spacecraft on board a Delta II rocket occurred from Cape Canaveral, FL, on August 4, 2007, at 5:26 AM local time. Arrival at Mars was on May 25, 2008, at 68 °N on the arctic plane 1 month before Mars summer solstice. Entry, descent, and landing, or EDL, are the most critical phase of the mission. It was accomplished by employing a parachute and retro-rockets. Operation on the surface is planned for 90 sols.

Summary

The thermal evolved gas analyzer, one of six instruments on the Martian Phoenix lander, consists of two components, a set of eight very small ovens that will heat samples of surface and subsurface ice-soil mixtures and a mass spectrometer that serves as the analysis tool for the gases evolved from the oven samples and also for measurements of the composition and isotopic ratios of the gases that comprise the atmosphere of Mars.

The mass spectrometer is a rugged miniature magnetic sector instrument controlled by microprocessor-driven power supplies. The spacecraft is a lander with an arm and scoop designed to dig a trench through the top soil to reach an expected ice layer near the surface.

Table 1. Instrument parameters

Mass analyzer	Magnetic sector-field
Electron source	Thermal emission type
Mass ranges	4, extending from 0.7 to 140 Da
Mass resolution	m/Δm = 140 (highest mass range, others appropriate to the mass range)
All components of the MS are packaged together	
Volume	24 × 23 × 18 cm
Mass	5.7 kg
Operating power	13 watt



Figure 7. EGA instrument package.

Samples from various depths in the trench are deposited in the ovens and heated, first to melt any ice to release imbedded gases and then to 1000 °C to decompose their minerals and release tell tale gases. These gases are transported to the mass spectrometer for identification and abundance measurements as well as for determining the isotopic ratios of the principal gases.

The goals of the Phoenix mission are to verify the presence of water in the form of near subsurface ice, to characterize evolved gases, particularly for the presence of any organic materials, and to determine the mineralogy of the Martian soils. The mass spectrometer plays a key role in the accomplishments of these goals.

Acknowledgments

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