THE MARS '94 OXIDANT EXPERIMENT (MOx):
CREATION OF SOMETHING FROM NOTHING IN 1 YEAR

Arthur L. Lane
Mars '94 MOX Instrument Manager
Jet Propulsion Laboratory
Pasadena, California 91109

ABSTRACT

In December 1992 the Mars Oxidant Experiment (MOx) instrument was selected to be the U.S. contribution to the Russian Mars '94 mission by being included as part of the lander payload. T'he experiment is designed to investigate, characterize and understand the nature of the martian soil with respect to the presence of peroxides or superoxides and to test for the possibility of other kinds of chemical oxidants by examining time-related changes in various materials. MOx consists of 7 reaction cells, each of which have 9 small surface spots coated with materials thought to be sensitive to various types of oxidants. Five of these cells will be place in contact with the martian surface and two cells will be exposed to the martian atmosphere to measure gaseous reactions. Non-reactive spots in each cell provide controls to compensate for electronic drifts, thermal variations, and any mechanical perturbations. The entire instrument had to fit within virtually no remaining volume in the lander; not exceed 850 gms mass (< 2 lbs); consume virtually no power; require few, if any, commands; survive landing shocks at 250 g's; experience diurnal temperature variations of over 100°C and provide its own sequence and memory storage operations. This paper describes MOX and its capabilities, along with a view of the team approach to accomplish the effort in slightly over one year from dream to finished spaceflight hardware.

INTRODUCTION ANI) MEASUREMENT FOUNDATION

The Mars '94 Oxidant Experiment (MOx) is an effort to further investigate and understand the nature of martian soil and atmosphere, pursuing knowledge gained from the 1976 Viking 1 and 2 landers. A unique, small mass, low power instrument has been designed that will determine the oxidation activity level of soil and near-surface atmosphere which come into contact with a sensor probe placed upon the martian surface by two independent Russian Small Station Landers delivered by a Phobos-class spacecraft.

The mission, to be launched in October 1994 on a Proton launch vehicle, is scheduled to arrive at Mars in September 1995. Each Small Station is independently targeted to the martian surface about seven days before the Phobos orbiter spacecraft begins its orbit insertion maneuver. Each station lands semi-hard on an airbag cushion after an aeroshell/parachute descent. Approximately 10 minutes after landing the Small Station separates from the airbag landing system, chopping 30 to 50 cm to the Mars surface. Some 3-5 minutes later the petals open, providing an upright configuration for the station on the surface.

The scientific intent of this experiment is to measure the chemical activity of martian soil and atmosphere by examining the activity level of one or more compositionally unknown oxidants inferred from the Viking soil analysis experiments. The current working assumption is that the soil has been, and continues to be, oxidized by a photochemically induced process that produces H_2O_2 in the vapor phase near the surface. [1-4] This species subsequent y attacks rock surfaces, leading to an oxidized mineral content, Because energetic near-UV solar photons (as energetic as ~ 5.4 eV ($\lambda \approx$ 220 rim)) reach the martian surface during near-zenith passages of the sun each day, photo-activation processes can occur both directly on soil and rock mineral sites as well as in gases close to the surface. From the data acquired by Viking, some scientists have also postulated that other, non-peroxide or superoxide compositions are possible explanations for the Viking measurements. This experiment is designed to examine and bracket soil activity level to determine if the materials are peroxides or superoxides, to test for the possibilities of other kinds of chemical oxidants, and to examine loss of organic material due to chemical reactions with the martian environment.

The foundation of the experiment is based upon the initial work at Sandia National Laboratories on microchemical sensors.[5-7] These sensors, as initially developed, are sensitive photometers that examine the change in reflectivity of a semi-transparent film of material which is responsive to variations in its chemical environment. The changes can be as subtle as small alterations in the electron density in the conduction band of the sensor material or as large as physical corrosion or bulk oxidation changes. The Sandia approach is to coat or vacuum deposit the reactant onto the end of an optical fiber, and illuminate and detect via a splitter junction that connects to an optical source such as an LED and a detector such as a silicon diode or a photomultiplier. The modifications that the MOX approach brought was to multiplex and miniaturize the system using silicon micromachining procedures which permitted multiple reagent coatings in a single reaction cell and a common light source and detector structure for the multiple cells. The coating of the fiber ends was changed to a mass-produced approach of vacuum evaporator deposition or solvent casting onto a series of reaction cell surfaces so that uniformity and production of tens of units could be accomplished within a short interval.

DESIGN GOALS AND PERFORMANCE

The Russians plan a lifetime for the landed Small Station of about 1 Mars year (-2 Earth years). Based upon laboratory reaction rates for several metal films coated on fibers and inserted into superoxide simulated martian soils, measurable reactions are observable in several hours to several days. From these results, and the potential variety of film materials usable for this experiment, it appears that detectable changes will occur in 20 to 40 days on Mars, This experiment is designed to provide active measurements for at least 50 days on the surface, beginning with petal opening. Since the lander cannot provide power nor data transmission bandwidth until 10 to 40 days after landing, and then only sufficient for partial operation, the instrument requires batteries to enable stand-alone operation during the active chemical measurement portion of the instrument activity. The MOX data system will retain measurement data in memory, sustained by a separate long-lived battery, and will provide repeated transmissions of acquired early data and any subsequent data several times, supported by lander power, assuming the lander-orbiter pair lifetime exceeds 70 days.

To best utilize the limited data return from MOX it is extremely important to provide adequate controls and calibration sequences, Three specific sensors types were defined: a soil contact set, an atmospheric set, and a fully sealed group to act as an overall standard to account for electronic and thermal drifts as well as mechanical perturbations. The philosophy of a triple set to cover most variations is extremely important to the success of the overall experiment.

The experiment sensor, which in reality is a contamination sensitive probe, needs to be protected from handling and the outgassing environment of the small station and carrier spacecraft during their assembly, system testing, launch and cruise to Mars. The widest possible variety of fiber coatings, including several very reaction-sensitive metals, is desired so that the definitiveness of the experiment becomes sufficient to separate the different models of what the oxidant domain might be. The goal is to seal the atmospheric and soil sensor regions from contamination until the experiment is landed on the surface of Mars. This has been successfully demonstrated using -0.8 µm thick Si_3N_4 membranes over the cell reaction zones. These membranes have been tested to greater than an atmosphere pressure differential and have survived the 250 g shock landing profile.

The specific nature of the selected coatings which can be successfully transported to Mars. under the conditions imposed by this mission. leads to the determination of minimum performance and lifetime for this experiment. If the most desirable situation were possible. namely the ability to protect the coatings from the ambient environment until the lander reaches the Mars surface, then a minimum measurement lifetime of about 20 days with long-term data storage for eventual transmission to earth is reasonable. The Instrument Science Definition Team (ISDT) performed an initial analysis of the number of coatings necessary to provide a reasonable insight into the nature of the reactivity of the soil. Classes of materials examined were metals (Au, Ag, Al, Ti, Cu, ..), semi-conductor materials (Si, PbS, InAs, AlAs, ZnO, ..), metal ligand systems, and assorted organic materials. About 40 materials have been discussed so far, and the list was reduced to 18 active materials and 3 controls, with the realization that more coatings provide a better and more definitive assessment of the soil reactivity. In addition to the pure chemical reactivity aspect of the materials a number of other properties such as stability, air poisoning, sensitivity, coatability, etc., enhanced the selection of some materials over others.

Laboratory studies of coating materials of interest indicate that a super-oxidant material could react with several metallic films providing a 0.5 to 1 % change in optical reflectivity in a 5 to 15 day period. Based upon the modest laboratory results to date, the experiment needs to be able to detect a 0.2% reflectivity change, and measure, with about 20% accuracy, reflectivity changes in the 0.5 to 1.0% change range,

THE MOx INSTRUMENT

The MOX instrument design and configuration were dictated by the remaining resources available after the Lander was designed and ail the instrument interfaces were defined (mid- 1992), before anyone knew of the MOX instrument and its possible inclusion in the Lander payload. The most significant constraints imposed and design drivers were:

1. The volume available to the experiment and its scattered distribution within the lander, with the total mass of the experiment not to exceed 1000 gm (adversely affected by the distributed hardware placement);
2. Insufficient power available from the Small Station to run the full experiment and no power available for maintaining warmth of electronics or sensors;
3, Enforcement of the ITAR export regulations which significantly limited the capabilities of the instrument electronics (subsequently relaxed after MOX was completing fabrication);
4. Unknown time from landing for transfer of data from the experiment memory to the lander system for transmission to the orbiter for relay to Earth; and
5. Uncertainty in the effective bit error rate during transmission to Earth receivers.

The resulting design and configuration addressed these constraints and unknowns as best possible, within the additional programmatic constraints of low cost and tight schedule.

Technical Description

The MOX instrument is comprised of four principal components that achieve the necessary functionality:

1. The sensor head, which is deployed onto the surface of Mars by a boom identical to the one the Russians are supplying to the APX experiment. In the sensor head are the reactive film cells which interact with the martian soil and atmosphere, light emitting diodes (LEDs) that provide light sources for the films to reflect, a linear array detector which monitors the reflected light from each coating, and a preamplifier that conditions and drives the analog detector signals to the analog electronics box on the lander petal.
2. The analog and sequencer electronics box is located on the lander petal, within close proximity to the sensor head. In this box are the driver circuits for the LEDs, additional signal amplification, signal integration, the 12 bit analog-to-digital converter and timing circuits for the line array, integration control and ADC operation.
3. The CPU and power conditioning circuitry is located in a small box sandwiched between the APX instrument electronics and the Small Station instrumentation frame (space generously provided by the APX experiment). Within this single box are the 87C522 CPU/microcontroller, the program and data memory, data line interface to the Finnish Small Station Data Processing Unit (SDPU), watchdog and sequence timers, the dual real time clocks, engineering data conditioning & scaling, and the power conditioning electronics.
4. The battery box contains the sets of primary power cells that drive the experiment and a single

memory backup power cell. It is located external to the instrumentation frame, inside the insulating foam and near one of the Russian radio-isotope thermoelectric generator (RTG) units.

The physical instrument hardware placement on the small lander is shown in figure 1 and the kinder itself in figure 2. A simplified fiber optic configuration of the sensor head is presented in figures 3, with a photograph of a sensor head as figure 4. The overall measurement strategy is figure 5.

1. Sensor Head

The sensor head, which is placed gently onto the martian soil by the Russian built deployment boom, contains all of the active sensors for the MOx experiment (figure). Two varieties of chemical sensing cells are incorporated in this head: a first set of cells with thin film reactive coatings which either contact or come within about a millimeter or two of the soil, and a second set of cells with thin film coatings which are exposed to the Mars atmosphere to study its chemical activity. There are 5 of the first set of cells that contact the soil in the current implementation; more cells are possible in future units (could accommodate up to 13 in the present configuration). Within each cell there are three standard or reference coatings which monitor changes caused by temperature variations, thermal/mechanical stresses and changes in the total optical sensing system. Redundancies are possible through a matrix of locations. The atmospheric sensors, located on the top of the sensor head, are similarly constructed cells, two total in the present design with room for six total in future implementations, each with 9 different reactive coatings and 3 control coatings.

The photometer light source for the measurements is two LEDs which are located at one end of the sensor head. Dual wavelengths are used in this system to provide discrimination between mechanical and thermal changes in the coatings and different optical interactions with the band-gap energies of the thin film materials. Each LED shines into a common lightpipe that distributes the energy into fibers which go to each coating within each cell. In the present implementation of MOX, 84 spots or zones are illuminated simultaneously by each ‘on’ cycle of each LED.

The detection of the reflected light is accomplished by a 256 element silicon linear array which is coupled to optical fibers from each thin film coating zone. The array integrates the reflected light from all coatings separately and simultaneously, with the total integration time set to achieve a 60 to 70% full well capacity in each pixel. The data are multiplexed from the linear array by control electronics located in the petal electronics box, with the analog output conditioned by a differential amplifier located adjacent to the linear array, for transmission by wire to the integrator and analog-to-digital converter located in the petal electronics box. One temperature sensor monitors the changing thermal environment for the sensor head, which differ from that found in other places on the lander.

2. Analog and Sequencer Electronics Box on the Petal

The electronics box, located on the petal surface next to the deployment boom, provides:

1. Generation of necessary clock pulses and signals to operate the linear array, integrator and ADC;
2. Drive current for the selected LED used for each measurement;
3. The receiving end of the differential amplifier for the analog signals coming from the linear array in the sensor head;
4. Integrator and its reset circuitry; and
5. The conversion of analog data to digital format via a 12-bit linear ADC.

A temperature sensor is located near the ADC chip to provide monitoring of that critical area’s temperature swings for use in calibration of the received data,

3. CPU Box

The CPU box is located between the APX instrument electronics and the top of the instrumentation frame within the lander. The box is divided internally into two electromagnetically isolated areas -- the power conditioning area and the CPU, real time clocks, and memory area. The power conditioning electronics takes the 10.5 volts generated by the triad stacks of lithium batteries (located in the battery box) and regulates it down to +5 volts to be used in all the circuitry within MOX. The power conditioning electronics are switchers to provide the necessary efficiency. In order ensure . noise immunity these components are isolated from the other electronics in the CPU box by separate ground planes and the previously mentioned isolated areas.

The CPU, real time clocks, timers, memory and engineering, data conditioning/scaling amplifiers are located in the other compartment within the CPU box. This circuitry controls the MOX operations:

1. Recording of the engineering housekeeping data for the understanding of instrument performance;
2. Calculation of the sequence and start time of the data acquisition operation;
3. The receipt and interpretation of special commands and events signals;
4. The initiation of the timing circuits found in the analog and sequencer electronics;
5. The initiation of data sampling and its loading into memory space;
6. The retrieval of data from memory to be queued for transmission when requests come from the SDPU for data transfer; and
7. The selection of which data are to be sent and how many times, operating from the metric established prior to launch.

4. The Battery Box

The battery box contains three sets of three series-connected lithium batteries and one memory keep-alive battery. The box is mounted outside the instrumentation frame, but is bolted directly to the side of the frame near one of the Russian RTGs. These particular batteries were selected for their ability to deliver power at temperatures below -30°C once properly conditioned. The energy capacity of the three sets should be sufficient to provide MOX operation for between 50 and 70 days, with a factor of -2 margin, given the present estimated power levels utilized by the experiment, Once these batteries have been drained to the point where the power conditioning circuitry in the CPU box can no longer maintain +5 volt regulation, the active measurement aspect of the experiment is terminated and the remaining function of stored data transfer to the Lander central computer/sequencer (SDPU) occurs only when the SDPU provides the minimum power required to run the MOX digital circuitry.

5. Environment

The lander has two internal radioactive heater units that should provide a thermal environment that does not have the extrema of the ‘normal’ Martian day. The late summer - early fall landing season at latitudes 25 - 40” N imply that the external sensor head and petal box will see a peak. day temperature around -20 to -30° C and a dawn temperature of around -95 to -105° C. The electronics in the petal box and sensor head were designed and tested for operation below -90” C; however, not all components are NASA Class S parts. The thermal environment of the CPU and battery box should be more benign: -35 to +35° C. These units were tested for operation from -50 to +45° C.

The launch environment is that of the Russian Proton. The assemblies were tested to 9.7 g rms random shake and for pyroshock in each axis. In addition, the sensor head design was subjected to a 230 g, 3.5 ms duration drop test.

MOX INSTRUMENT OPERATION

Measurement Initiation

Surface science and engineering measurements are activated by a signal from the SDPU indicating the lander has contacted the surface. A hard-coded sequence is used and at a specified time after landing and prior to petal deployment, the instrument begins its internal calibration and measurement sequence which continues through petal opening. Following that, the instrument enters into its reaction rate measurement mode, as described in the following sections (see figure 5 for overall scenario).

After the petals have opened the MOX instrument boom is deployed, causing the sensor head containing the reaction cells to extend away from the lander, pulling and shattering the Si_3N_4 protective membranes fastened over the reaction cells. Boom deployment ends when the soil head comes into contact with the surface. Boom deployment occurs in approximately three (3) seconds.

Measurement Modes

There are three measurement modes employed, The first involves calibrations which occur before the boom is deployed and the reaction cells are exposed to the Martian environment. These are complete measurements requiring 32 seconds to finish a single measurement cycle. The complete calibration utilizes 2 cycles prior to Mars atmosphere entry some 6 days after lander separation from the Phobos orbiter stage; 1 cycle post-landing, but prior to petal opening; and 1 cycle post petal opening, but prior to boom deployment. This strategy examines the survival of the protective membranes and the electronics before entry (launch and cruise survival) and after landing (survival after the -200 g landing shock and subsequent bounces) and establishes the basis for any electronic offsets in the measurement data which will follow.

The second mode involves a short series of quick mini-cycle measurements which are taken as the boom deploys and the sensor head reaches the surface. These are six measurement mini-cycles that occur over a 24 second period.

The third mode is the basic, long duration measurements that begin about 28 seconds after boom deployment begins, 4 seconds after the 2nd mode ends, and continues until the entire memory buffer is filled. The measurement strategy involves a set of discrete timing starts for each measurement cycle for the first day of landing, and a periodic structure for days after that. For Day O the time between measurement cycles follows a logarithmic-like function of decreasing measurement cycles per unit time. Day 1 has ten cycles evenly spaced over the Mars day. Days 2 through 5 have five non-uniformly spaced measurement cycles per day, but each day is identical in its timing. Days 6 through 10 have four non-uniformly spaced measurement cycles per day and again, each day is identical in its timing. The next period covers days 11 through 20 with two measurement cycles per day focused on the hottest part of the daily temperature cycle, about 12:30 to 13:00 local and then at about 19:30 to 20:00 when the temperatures have not dropped to too cold a level but there is no significant sunlight present. Days 21 through 40 continue the same pattern as in days 11-20, but active only on alternate days to avoid filling the last 90% of memory too quickly. After 40 days the pattern continues every 3rd day, but only when there exists memory into which to place new measurements. Memory is allocated to new measurements once the data have been properly sent for transmission according to a priority ordered transmission table resident in the MOX software.

Each measurement cycle consists of four subunits of optical reflectance measurements: amber - low intensity, near IR - low intensity, amber - high intensity and near IR - high intensity, in that order. For each subunit, there are 8 co-added readings from the line array, accomplished in the following manner: clear the array twice to remove residual charge, then for each pixel of the 256 pixel array 8 consecutive sets of 12-bit data (illumination measurement minus dark measurement) are co-added into a 16-bit register. That number is saved and stored. This pattern is repeated for each color and intensity level (low and high, which differ by about a factor of 5). At the start of each major sequence block (day 1, day 2, day 6, day 11, and day 21) a separate dark reading is performed and stored with the data to be returned to earth.

After the probe has landed but prior to instrument primary battery consumption, the instrument will collect and store data. After 20 to 40 days the SDPU will query the instrument for data, depending upon the orbiter's availability. Transferring data to the SDPU takes priority over all other events. Data transfer requests interrupt any measurement cycle, causing the cycle to resume once data transfer has been completed, Science data are transferred along with engineering data. Frequency and duration of the transfer operation is totally determined by the SDPU and data volume per unit time will be determined by the lander's main "cyclograms" (sequences) to be constructed during the spring of 1994.

The instrument analog electronics become unavailable upon depletion of the MOx primary batteries. No instrument measurements are attempted after the primary batteries reach a voltage condition that is too low to drive the power conditioning circuitry and safely run the instrument. Once this occurs, the extremely limited power from the lander is provided to operate the instrument's internal digital electronics which enables transfer of stored data one or more times. A memory backup secondary battery is provided to ensure no data loss during the useful lifetime of the station.

PROGRAMMATICS AND THE MOx TEAM

The Mars '94 Small Station Lander has a strong international flavor with its participants spread across Russia, France, Finland, Germany and the United States. The initial conditions for the inclusion of MOX onto the Mars '94 Lander payload were extremely daunting. With the good will created by strong cooperative desires among the participants it has been possible to integrate the MOX into this mission. This required the Finns and the Germans to find a way to allow MOX to share a common command and data line with the APX instrument and generate a modest number of MOx-specific coded commands. It required the Russians to fabricate, with the assistance of the Germans, another deployment boom similar to that used by the APX but with a slightly different latching mechanism. Internal volume was at a premium; only because the Germans were able to use less electronics inside the lander and to shorten their electronics box was MOX able to sandwich its CPU box between the APX and its mounting place on the lander internal structure, and the Russians agreed to allow MOX to place its battery compartment (because there was no extra power available to run MOX) outside the internal frame within the thermal insulation of the lander. These and many other small to moderate compromises and assists enabled MOX to be able to be an active part of the lander payload. Only through diligent work and strong inter-personal relations were the necessary changes achieved; to the credit of all the participants.

The development of the Mars '94 MOX experiment represented a significant departure from the mode in which most Jet Propulsion Laboratory spaceflight experiments were developed in the past. These changes covered areas such as team formation and interactions, procurement methodology, continuity of individuals throughout the design, build and test phases, tremendous flexibility in design change because the receiving organizations (Russia's science and engineering offices on Mars '94) often changed interfaces without timely notification and extensive use of handwritten or handdrawn documentation.

A small team led the design, fabrication and testing of the MOX instrument, An overriding principle was that members of the team had to be multi-disciplinary in order to provide early vision of problems and potential solutions by working problems rather than 'tossing them over the fence' .Co-location of personnel into three major elements reduced communication delays substantially as well as providing a forum for rapid interactions with diverse technical talent during the formative stages of the design and fabrication. These elements were: 1) The project office which included the project manager, schedule & fiscal support, the instrument manager (whose roles also included acting as the local Principal Investigator and calibration test lead), the deputy instrument manager (who oversaw the electronics fabrication, task scheduling details, interfaces with mechanical and software functions, and provided contract management direction for the electronics fabrication), the mechanical lead engineer, the software/sequence engineer (CPU, support equipment, and sequence programming, as well as test plan support) and the secretarial/procurement support; 2) The breadboard and testing laboratory area where the initial electronic designs and battery concepts were developed and the complete thermal/vat testing program occurred; and 3) The Microdevices Laboratory (MDL) where the sensor technology for MOX was conceived, iteratively fabricated and finally assembled, In addition to the JPL domain, two major local industrial partners assisted in the MOX development, Loral EOS with the electronics final design, build & vibration testing and OCA Applied Optics for the fiber optic harness structures and optical assembly. In all cases, rapid communication and strong personal interactions permitted schedule flexibility and trade-space solutions to be achieved quickly with minimized cost impact. Although not a true 'Skunk Works' the MOX team extracted and used many of the concepts matured by Lockheed and Kelly Johnson in their now-famous operational unit. Throughout the design, fabrication and testing the NASA instituted Instrument Science Definition Team for MOX provided interaction with the design, guidance through several painful decision processes that led to descoping because of schedule pressures, and encouragement as everyone worked together to create a totally new class of instrument for planetary exploration in about one year and for about $4M.

ACKNOWLEDGEMENT

The research described in this paper was performed, in part, by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. Klein, H. P.,''The Viking biological experiments on Mars", *Icarus*, 34, 666-674, 1978.
2. Klein, H. P.,''The Viking Mission and the search for life on Mars", *Rev. Geophys. & Space Phys,* 17,1655-1662,1979.
3. Zent, A.P. and C.P. McKay, "The chemical reactivity of the martian soil and its implications for future missions", *Icarus*, in press.
4. Hunten, D. M., "Possible oxidant sources in the atmosphere and surface of Mars", *J. Mol. Evol.*,14,57-67,1979.
5. Butler, M.A. and Ricco, A. J., "Chemisorption-induced reflectivity changes in optically thin silver films", *Appl. Phys. Lett.*, *53,* 1471-1473, 1988.
6. Butler, M. A., "Optical fiber interferometric sensors for chemical detection", SPIE, 1368, Chemical, Biochemical and Environmental Fiber Sensors II, 46-54, 1990.
7. Butler, M.A. and Ricco, A. J., "Reflectivity changes of optically-thin nickel films exposed to oxygen", *Sensors and Actuators, 19, 249-256, 1989.*

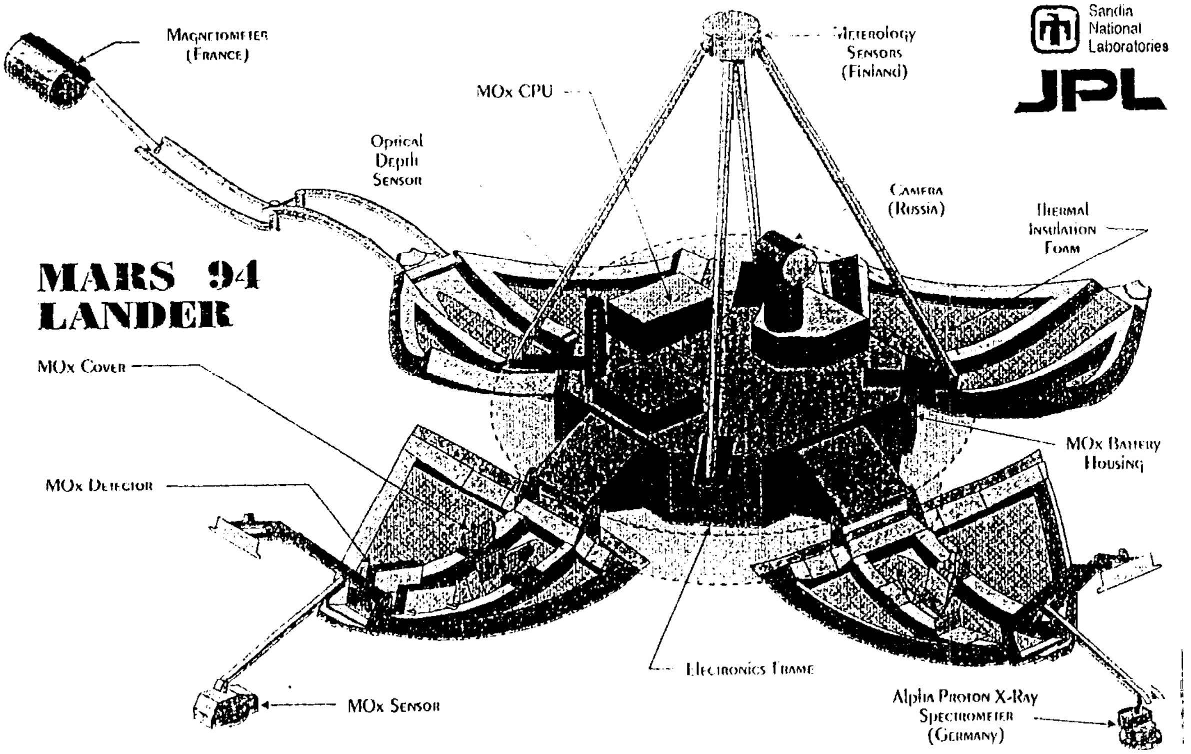

Figure 1. Pictorial depiction of the small station lander, after deployment of the petals and the booms. Instruments and major elements are labelled .

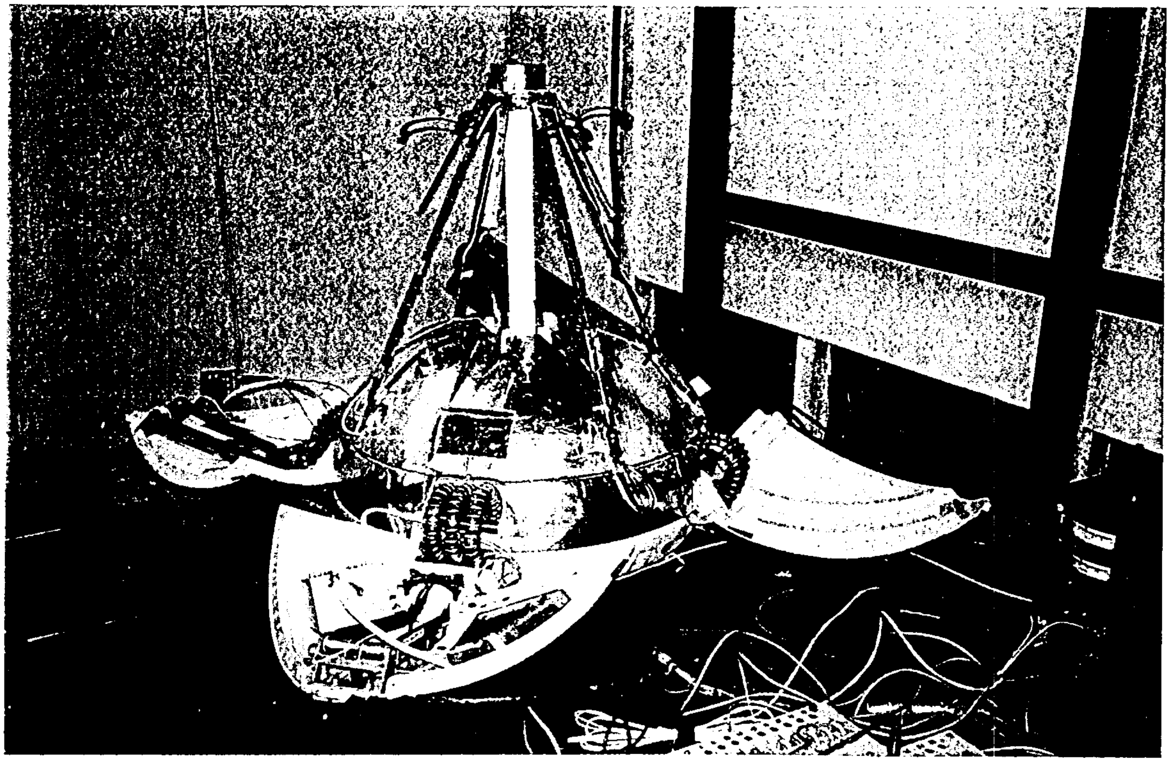

Figure 2. Photograph of the small station lander. Lander is about 60 cm in diameter. with petals closed. MOx sensor and analog electronic box are mounted on the petal in the foreground. The MOx deployment boom is in the center of the petal. in its 'caged' configuration.

Mars '94 Oxidant Experiment Optical Configuration

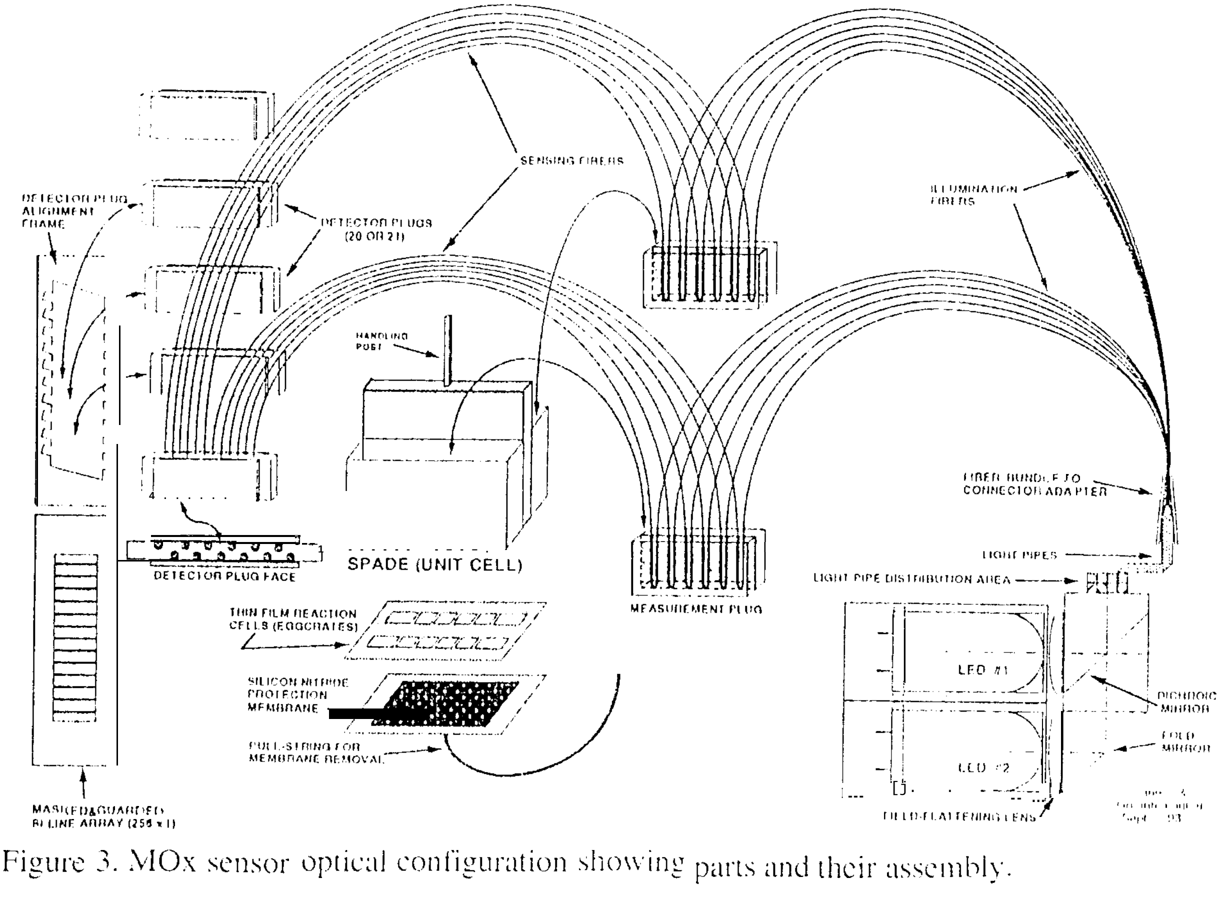

Figure 3. MOx sensor optical configuration showing parts and their assembly.

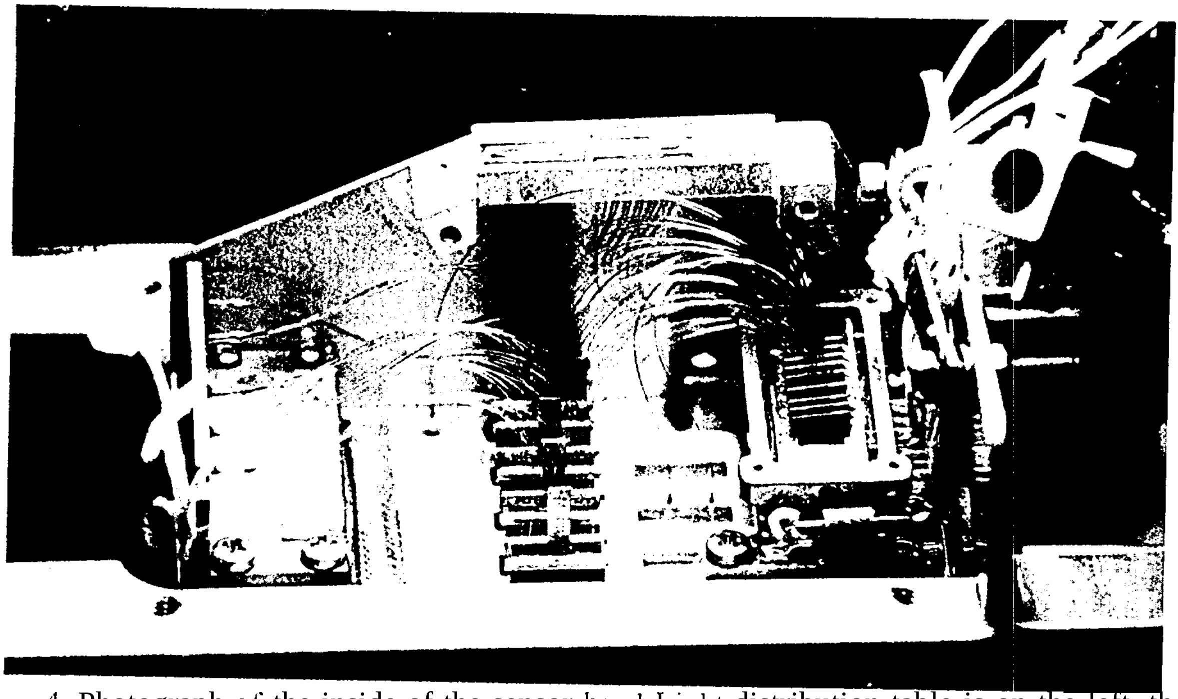

Figure 4. Photograph of the inside of the sensor head. Light distribution table is on the left, the line array detector is on the right. Soil cells face downward in the center. atmosphere cells upward (top of photograph). The optical fibers between light source. measurement cell and detector can be seen as loops of fibers. Cell is about 7 cm long, 3 cm wide and 4 cm tall.

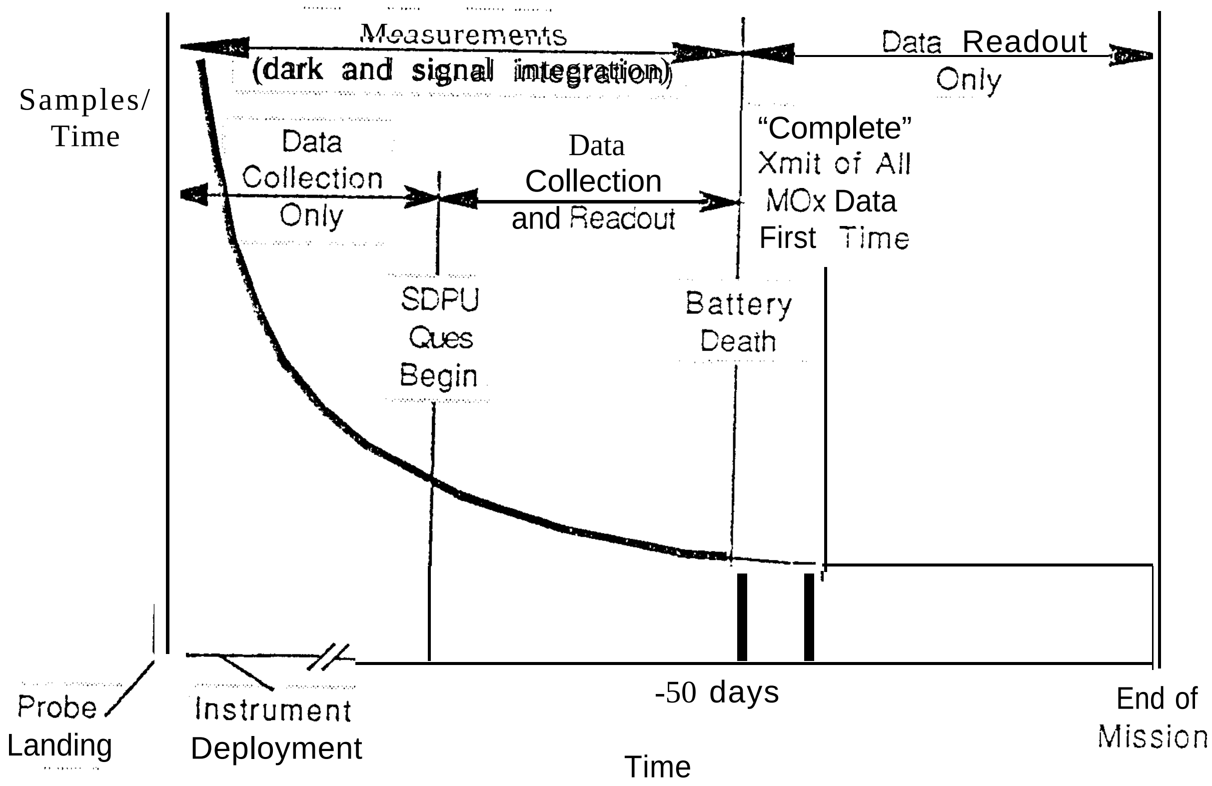

Figure 5. Overall operational strategy. Measurements are only performed while the primary batteries are alive, and the density of measurements decreases logarithmically with time to emulate a reaction rate measurement experiment.