The 2001 MARS IN-SITU-PROPELLANT-PRODUCTION PRECURSOR (MIP) Flight Demonstration

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1. Introduction

Strategic planning for human missions of exploration to Mars has conclusively identified in-situ propellant production (ISPP) as an enabling technology. A team of scientists and engineers from NASA Johnson Space Center, Jet Propulsion Laboratory, NASA Glenn Research Center, and the University of Arizona is preparing the MARS ISPP PRECURSOR (MIP) Flight Demonstration[1]. The objectives of MIP are to characterize the performance of processes and hardware that are important to ISPP concepts and to demonstrate how these processes and hardware interact with the Mars environment. Operating this hardware in the actual Mars environment is extremely important because uncertainties in our detailed knowledge of the Mars environment make it impossible to adequately simulate that environment on Earth.

The MIP Flight Demonstration is a payload onboard the MARS SURVEYOR Lander and is scheduled to be launched in April 2001. MIP will be the first hardware to utilize the indigenous resources of a planet or moon. Its successful operation will pave the way for future robotic and human missions to rely on propellants produced using Martian resources as feedstock.

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[1] The MIP website is found at http://spaceflight.nasa.gov/mars/technology/mipp/index.html

2. MIP Overview and Objectives

MIP is comprised of five distinct experiments; their names and key objectives are:

- **MARS ATMOSPHERIC ACQUISITION AND COMPRESSION (MAAC)**: to selectively absorb and compress carbon dioxide from the Martian atmosphere;
- **OXYGEN GENERATOR SUBSYSTEM (OGS)**: to produce propellant-grade, pure oxygen;
- **MARS ARRAY TECHNOLOGY EXPERIMENT (MATE)**: to measure the solar spectrum at the Mars surface and to test several advanced photovoltaic solar cells;
- **DUST ACCUMULATION AND REPULSION TEST (DART)**: to investigate the properties of dust and to test techniques to mitigate the settling of airborne dust onto solar arrays; and
- **MARS THERMAL ENVIRONMENT & RADIATOR CHARACTERIZATION (MTERC)**: to measure the night sky temperature and to demonstrate the performance of radiators.

The MIP package will be small and lightweight. Its overall external envelope is approximately 40 x 24 x 25 cm (15.7 x 9.4 x 9.8 inches), and its mass is less than 8.5 kg (18.7 lbm).

The long-term effects of operating in the Martian environment are key information being sought by MIP. Therefore, MIP would like to operate for a lifetime of 90 sols[2] or more on Mars.
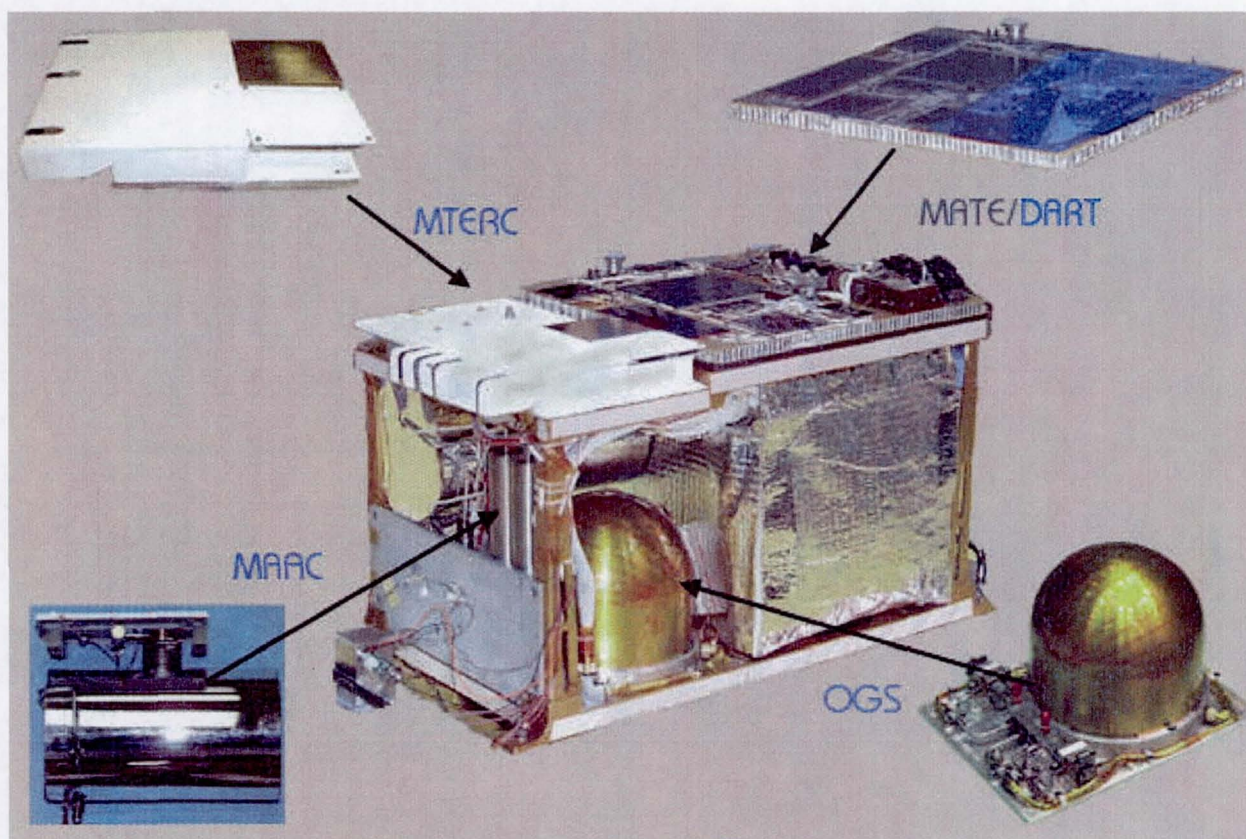
Photograph of integrated MIP Development Unit

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[2] A "sol" is the length of a mean solar day for Mars; that is, 24 hours and 37 minutes.

3. Mars Atmospheric Acquisition and Compression (MAAC)

The MAAC experiment is being designed and fabricated at the Jet Propulsion Laboratory. The Co-Investigator for MAAC is Paul Karlmann (Paul.B.Karlmann@jpl.nasa.gov). The MAAC and MTERC Project Manager is Ken Johnson (Kenneth.R.Johnson@jpl.nasa.gov).

Photograph of MAAC Qualification Unit

3.1 Rationale

The most readily available resource on Mars is the atmosphere. Hence, carbon dioxide (CO_2), which makes up more than 95% of the atmosphere, is the primary resource being considered for early Mars missions. However, the Mars atmospheric pressure is only 6 to 10 torr (0.1 to 0.15 psi), whereas most ISPP processes operate at approximately 760 to 3800 torr (14.7 to 73.5 psi; 1 to 5 atm.). Therefore, a CO_2 collection and compression device is required that is relatively small, lightweight, power efficient, tolerant to dust contamination, rugged and reliable enough to operate for long periods under the severe daily and seasonal temperature variations of Mars.

MIP will demonstrate CO_2 collection and compression using a **sorption compressor**. A sorption compressor contains virtually no moving parts and achieves its compression by alternately cooling and heating a sorbent bed comprised of materials which absorb low pressure gas at low temperatures and desorb high pressure gas at higher temperatures. Due to the lack of rotating/moving parts, it has significant potential for high lifetime, reliability, and robustness. The characteristics of the sorbent bed material in the sorption pump define how much gas can be absorbed and which species are more readily absorbed over others. The MAAC sorbent bed material is chosen to be 13X-Zeolite in order to provide the required preferential affinity for CO_2.

3.2 Primary Goal

The primary goal of the MAAC experiment is to demonstrate and characterize the acquisition and compression of atmospheric carbon dioxide (CO_2) using a sorption compressor on Mars.

3.3 Objectives

In order to achieve its primary goal, MAAC will accomplish the following objectives:
- Acquire CO_2, principally during nighttime, from the Martian atmosphere.
- Deliver at least 4.5 grams of compressed CO_2 during 6 hours of daytime operation to the Oxygen Generator Subsystem (OGS).
- Deliver the CO_2 to the OGS at a pressure of 440±52 torr (8.5±1 psia) and at a flow rate of 3.0±0.5 sccm.

3.4 Overview Description

MAAC acquires CO_2 during the cold Mars night when temperatures are typically 200°K. Beginning at nighttime and lasting for up to 65 hours (that is, 3 nights and 2 days), a bed of 13X-zeolite sorbent material is passively exposed to the atmosphere by opening two small valves. The bed absorbs CO_2 by diffusion from the 6 torr atmosphere. Once an adequate amount of CO_2 has been absorbed (~4.5 g), the valves are closed and the sorbent bed is heated. Heating occurs only during daytime when energy from the Lander's solar arrays is available to power MAAC's heaters. The temperature of the bed is raised to roughly 450°K. As the temperature of the sorbent material rises, more and more CO_2 gas is desorbed. Heating the sorbent bed in its restricted-volume canister will cause the CO_2 gas to build to a higher pressure. Well before 450°K is reached, carbon dioxide pressure in the canister will have climbed to 440 torr. At that pressure, the CO_2 is fed to the OGS experiment. Additional heating up to 450°K is performed at a rate so as to maintain the 440 torr pressure.

4. Oxygen Generator Subsystem (OGS)

The OGS experiment is being designed and fabricated at the University of Arizona under contract to the NASA Johnson Space Center. The OGS Project Manager at the Johnson Space Center is R. Scott Baird (r.s.baird@jsc.nasa.gov). The OGS Co-Investigator at the University of Arizona is K. R. Sridhar (krsridhar@mail.arc.nasa.gov).

4.1 Rationale

The ultimate objective of any ISPP demonstration is to produce useful products from the surrounding environment. Oxygen is one of the most useful products needed for future exploration missions with applications in rocket propulsion as a propellant, in fuel cell power generation as a reactant, and in life support as a breathing gas. The OGS will produce pure, propellant-grade oxygen from Martian atmospheric carbon dioxide (CO_2).

4.2 Primary Goal

The primary goal of the OGS is to demonstrate the production of oxygen from Martian atmospheric carbon dioxide.

4.3 Objectives

In order to achieve its primary goal, OGS will accomplish the following objectives:
- Use Martian atmospheric CO_2 provided by the MAAC experiment;

- Verify oxygen gas is produced at a rate of at least 0.5 sccm for each operation;
- Operate at least 10 times over 90 sols on Mars;
- Determine the long-term changes in performance of zirconia solid-oxide oxygen generation hardware in the Mars environment.
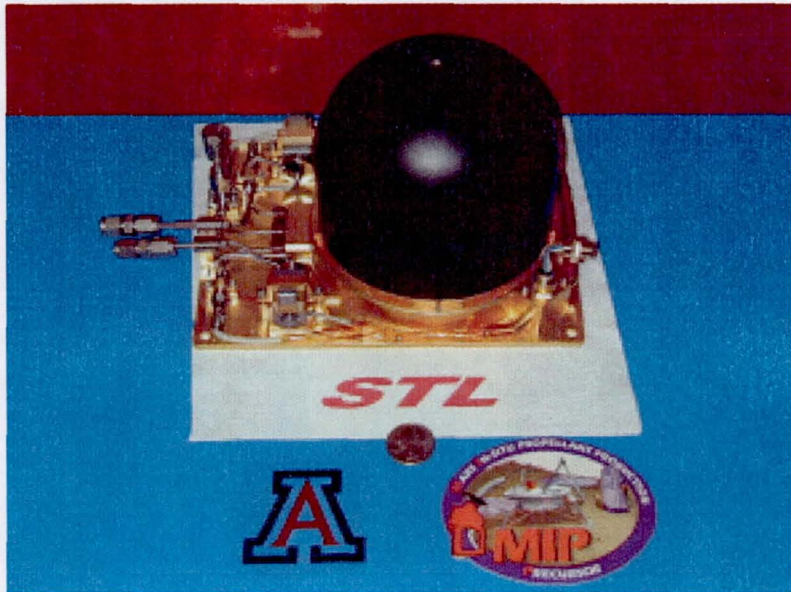
Photograph of OGS Qualification Unit

4.4 Overview Description

The heart of the OGS is a zirconia solid-oxide oxygen generator. This generator produces oxygen by electrolyzing CO_2 feed gas at elevated temperatures (1023°K) to strip off an oxygen ion from the carbon dioxide molecule. Once the oxygen ion has been removed from the CO_2 molecule, it is drawn through the zirconia oxide membrane by an applied voltage across the membrane. On the other side of the membrane, the ion gives up an electron to become an oxygen atom and then combines with another oxygen atom to form O_2 gas. The unique crystalline structure of zirconia oxide allows only oxygen ions to travel through the material. The zirconia oxide generator is in fact a solid state oxygen pump and separator that, in the case of the OGS, is sized to produce a minimum of 0.5 standard cubic centimeters per minute (sccm) of O_2. The OGS will be operated at least 10 times on the Martian surface.

4.5 References

R. S. Baird, K. R. Sridhar, and M. Gottmann, *2001 Mars In-Situ Oxygen Production Flight Demonstration*, AIAA 99-2413, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, June 1999.

5. Mars Array Technology Experiment (MATE)

The MATE experiment is being designed and fabricated at the NASA Glenn Research Center. The Co-Investigator for MATE is David Scheiman (David.Scheiman@grc.nasa.gov). The MATE and DART Project Manager is Cosmo Baraona (Cosmo.R.Baraona@grc.nasa.gov).

5.1 Rationale

While the use of ISPP will dramatically reduce the overall Earth-launch mass for both a human mission and a robotic Mars Sample Return mission, the power requirements for ISPP operation can be significant. This necessitates the use of advanced photovoltaic cell technology to mini-

mize power system mass. However, the long-term performance of advanced photovoltaic cell and array hardware in the Mars environment is not known and cannot be adequately tested on Earth. For example, sunlight on the surface of Mars is altered by airborne dust and fluctuates from day to day. The dust affects both the intensity and spectral content of the sunlight.
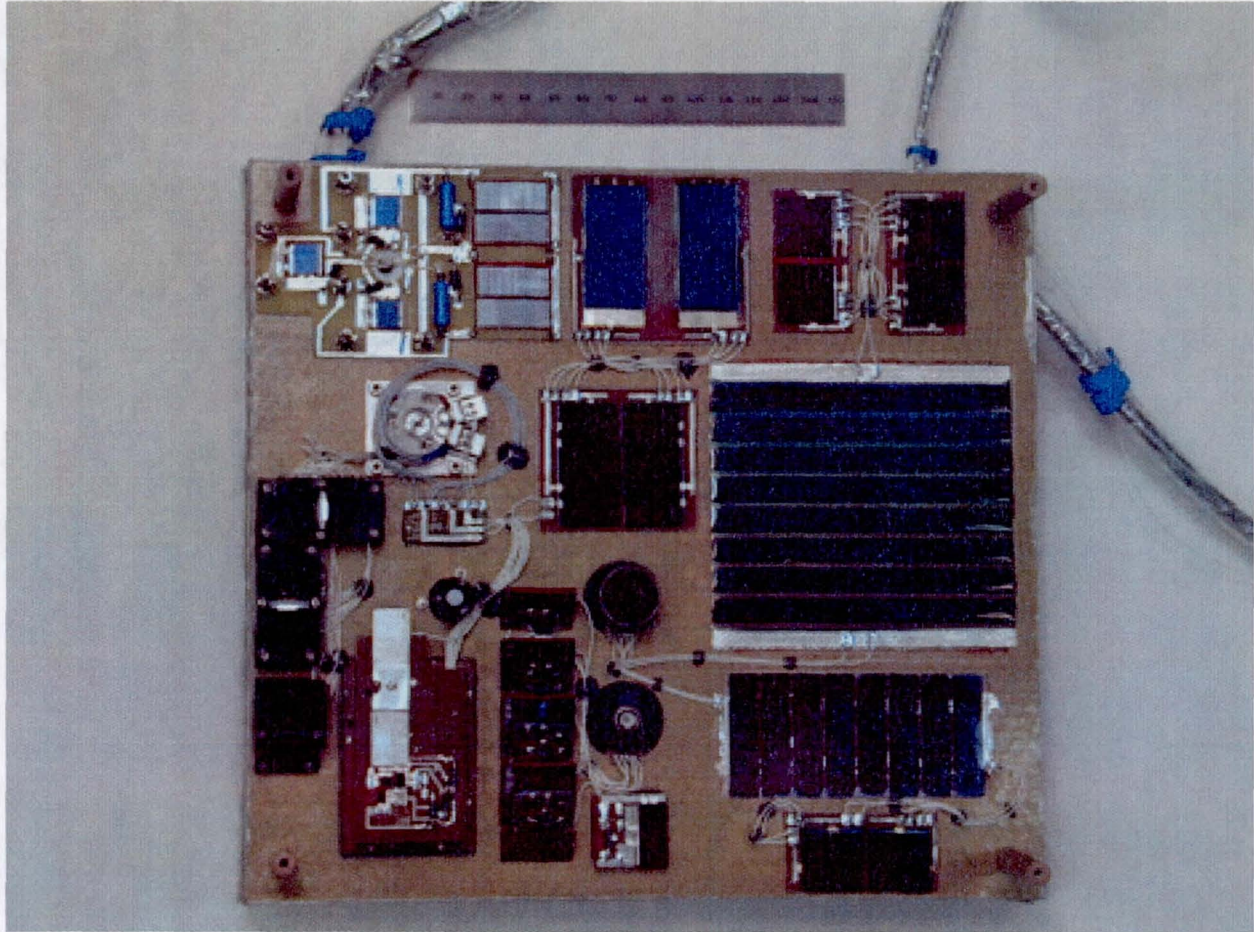
Photograph of MATE and DART Qualification Unit

5.2 Primary Goal

The primary goal of MATE is to determine the optimum solar cell type for future robotic and human missions to Mars.

5.3 Objectives

In order to achieve its primary goal, MATE will accomplish the following objectives:

- Measure the performance of different solar cell types in the Martian environment;
- Study long-term effects of dust on solar cell performance; and
- Characterize the Martian environment for solar cells by measuring:
    → Solar insolation (both direct and global)
    → Solar spectrum
    → Solar cell temperature

5.4 Overview Description

MATE will incorporate five different individual solar cell types, two different solar cell strings, and temperature sensors to characterize promising solar cell materials and designs. MATE will also incorporate two radiometers and a dual spectrometer. The dual spectrometer will measure the global solar spectrum from 300 to 1700 nm by incorporating two separate photodiode arrays each with its own fiber optic feed and grating. Besides measuring the solar spectra on Mars, the dual spectrometer will also identify dust absorption and reflection bands, quantify daily variations in spectra and intensity, and improve atmospheric modeling.

5.5 References

D. A. Scheiman , M. Krasowski, L. Greer, D. Spina, C. Baraona, D. Wilt , P. Jenkins, and G. A. Landis, *Mars Array Technology Experiment (MATE) for the 2001 Lander*, Proc. 2nd World Conference on Photovoltaic Energy Conversion, Vienna, Austria, July 1998. http://powerweb.lerc.nasa.gov/pvsee/publications/wcpec2/mate2001.html

G.A. Landis, *Solar Cell Selection for Mars*, Proc. 2nd World Conference on Photovoltaic Energy Conversion, Vienna, Austria, July 1998.
http://powerweb.lerc.nasa.gov/pvsee/publications/wcpec2/cells4mars.html

6. Dust Accumulation and Repulsion Test (DART)

The DART experiment is being designed and fabricated at the NASA Glenn Research Center. The Co-Investigator for DART is Geoffrey Landis (Geoffrey.A.Landis@grc.nasa.gov). The MATE and DART Project Manager is Cosmo Baraona (Cosmo.R.Baraona@grc.nasa.gov).

6.1 Rationale

Large amounts of dust are raised into the atmosphere of Mars by dust storms. Atmospheric dust consists of relatively small (micron scale) particles, suspended at altitudes of up to 20 km. This dust settles out the atmosphere onto any horizontal surface. Dust deposition could be a significant problem for photovoltaic array operation during long duration missions on the surface of Mars. Measurements made by the PATHFINDER mission showed a 0.3% loss of solar array performance per day due to dust obscuration. This is potentially the major lifetime-limiting factor for a solar-power system on any Mars mission which is required to last for longer than 100 days, unless a technique is developed to periodically remove the dust or prevent settled dust from coating the array.

6.2 Primary Goal

The primary goal of DART is to prevent degradation of solar array performance on Mars due to dust.

6.3 Objectives

In order to achieve its primary goal, DART will accomplish the following objectives:

- Measure the power loss of solar cells on Mars due to settling of airborne dust;
- Measure the characteristics of deposited dust; and
- Test methods of preventing dust accumulation by:
    - → Elecrtostatic dust repulsion
    - → Titled surfaces

6.4 Overview Description

DART will gather engineering data about the deposition rate and properties of the dust. It will utilize a microscope, a dust accumulation monitor, and a sun position sensor package. The microscope will measure the rate of dust deposition, the particle size distribution, the particle opacity, the particle shapes, and possibly information about the particle composition through measurements of the optical properties.

DART will include a *tilted cell* experiment. Observations of the thermal shell of the Viking Landers seemed to show that dust also did not build up on the tilted surfaces. Due to this observation, DART seeks to verify the conjecture that tilted solar cells do not accumulate dust, and to get an indication of what angle is required to avoid dust coverage. The tilted cell measurement consists of solar cells tilted at 30°, 45°, and 60°, a horizontal control cell, and a solar cell tilted at 30° with low friction (diamond-like carbon) coating.

DART also includes an electrostatic dust repulsion device. Martian atmospheric dust is expected to be charged. Instead of attempting to remove settled dust, the DART experiment will use high-voltage to attempt to repel the dust before it settles. A vertical multi-junction high-voltage solar cell will provide a potential of about 80 volts between a transparent conductor on the front surface of the solar cell coverglass and a thin wire used as a ground. The configurations tested will be positive potential applied to the cell cover, negative potential applied to the cell cover, and transverse field across the cell cover. These will be compared to a control horizontal cell with no potential applied.

6.5 References

G. A. Landis, P. P. Jenkins, C. Baraona, D. Wilt, M. Krasowski, and L. Greer, *Dust Accumulation and Removal Technology (DART) Experiment on the Mars 2001 Surveyor Lander*, Proc. 2nd World Conference on Photovoltaic Energy Conversion, Vienna, Austria, July 1998.
http://powerweb.lerc.nasa.gov/pvsee/publications/wcpec2/DART.html

7. Mars Thermal Environment & Radiator Characterization (MTERC)

The MTERC experiment is being designed and fabricated at the Jet Propulsion Laboratory. The Co-Investigator for MTERC is David Brinza (David.E.Brinza@jpl.nasa.gov). The MAAC and MTERC Project Manager is Ken Johnson (Kenneth.R.Johnson@jpl.nasa.gov).

7.1 Rationale

Thermal management is critical for efficient operation of an ISPP plant. Heat removal radiators will be required for such operations as cooling down a sorption pump (i.e., sorbent bed) and cooling oxygen and fuel before liquefaction and storage.

7.2 Primary Goal

The primary goals of MTERC are to determine the Martian effective sky temperature and the effects of the Martian environment on radiators and thermal coatings in order to design more reliable thermal systems for future robotic and human missions.

7.3 Objectives

In order to achieve its primary goal, MTERC will accomplish the following objectives:

- Measure the effective Martian nighttime sky temperature to $\pm 10°K$ of the actual value;
- Measure both the emissivity and solar absorptivity of exposed radiators to ± 0.05 of actual values;
- Determine the long-term rate of thermo-optical (emissivity and absorptivity) degradation of radiator surfaces, particularly due to coverage by settling dust.
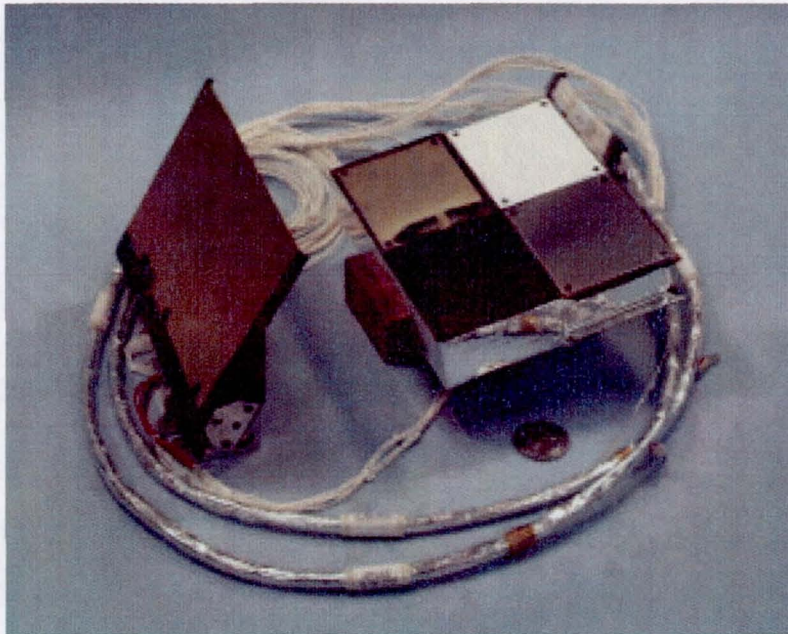
Photograph of MTERC Qualification Unit

7.4 Overview Description

The MTERC experiment will include four radiator plates: two with high emissivity and two with low emissivity. One high and one low emissivity plate will be protected by a movable cover and will serve as the experiment control radiators. These control radiators will experience the least degraded measurement of the effective Martian nighttime sky temperature and will serve as comparisons for the two continuously exposed radiators in order to examine the impact of dust accumulation, wind abrasion, etc., on long-term radiator performance.

MTERC typically operates with an *active/reference* plate pair. Initially, due to its higher absorptivity and lower emissivity, the exposed *reference* plate has a higher temperature than the *active* plate. The *active* plate is heated to the same temperature as the *reference* plate. The two

plates then radiate heat out into the Martian environment. The governing equation of interest is:

$$\Delta q = (\Delta \varepsilon)\sigma A(T_{plate}^4 - T_{Sky}^4)$$

where Δq = the known differential heating in Watts

A = the known radiator plate area

σ = the Stefan-Boltzmann constant

$\Delta \varepsilon$ = the emissivity difference of the radiator pair

T_{plate}^4 = the active plate/reference plate temperature

T_{sky}^4 = the Martian night sky temperature

For a clean radiator pair, the heat to be rejected (Δq), radiator plate areas (A), Stefan-Boltzmann constant (σ), emissivity difference ($\Delta \varepsilon$), and plate temperatures (T_{plate}) are all known; therefore, the nighttime sky temperature (T_{sky}) can be computed.

8. Conclusion

The successful performance of the five individual demonstrations of MIP will provide both knowledge of and confidence in the reliability of this technology. At the completion of this flight demonstration, the MIP Team will be able to:

- recommend preferred hardware configurations for the intake and adsorption of carbon dioxide from the Martian atmosphere;
- understand the performance characteristics of zirconia cells to generate propellant-grade oxygen;
- understand long-term performance characteristics of advanced solar cells/arrays operated in the actual Mars environment;
- evaluate the functionality of methods to mitigate the deposition of airborne dust onto solar arrays; and
- recommend preferred hardware designs for innovative thermal management including the radiation of heat to the outside environment.