MIP: the First ISRU Flight Experiment

Geoffrey A. Landis[1]
NASA Glenn Research Center, 21000 Brookpark Road, Cleveland OH 44135

The Mars ISPP Precursor, "MIP", was a flight experiment on the 2001 Mars Surveyor Lander that was designed to demonstrate In-situ Propellant Production-- ISPP-- for the first time on Mars. The experiment was designed to show that it was possible to produce oxygen from the carbon dioxide atmosphere, and to demonstrate the individual technology components that would go into a full-scale production plant. The aimpoint of the oxygen production was to showcase the possibility of producing oxygen for use as rocket fuel, ultimately as an enabling technology for a future human expedition to Mars. The MIP team built and qualified flight hardware for the experiment to fly on the Surveyor-2001 lander, but following the failure of the 1999 Mars Polar Lander spacecraft, the Surveyor-2001 lander mission was cancelled, and the MIP experiment was never flown. The experience in building and testing the hardware did show that the carbon dioxide electrolysis process was feasible, and led to incorporation of in-situ propellant production into the NASA reference plans for human Mars missions. Twenty years later, the technology is flying to Mars in the form of the MOXIE experiment on the Perseverance rover.

I. Introduction

Although early concepts for human exploration of Mars proposed bringing the propellant for the return voyage from Earth, more recent exploration concepts have shown that exploration of Mars could be far more effective if the local resources of the planet could be used to manufacture the fuel for the return voyage ("in-situ resources utilization", or "ISRU") [1]. ISRU for fuel production, or In-Situ Propellant Production ("ISPP"), can significantly reduce the mass required to be launched from Earth and landed on the planet, and thus may be an enabling technology for Mars exploration. Since oxygen is the largest (by mass) fraction of rocket fuel, the generation of oxygen is the most critical need.

In 2021, the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) will land on Mars as part of the Mars "Perseverance" rover's experiment package [2], and for the first time will demonstrate the use of in-situ resources of another planet, by using the carbon dioxide atmosphere of Mars as a feedstock to produce oxygen.

MOXIE, however, was not the first flight experiment proposed to test in-situ resource utilization (ISRU). The Mars ISPP Precursor, "MIP", was a flight experiment on the 2001 Mars Surveyor Lander that was designed to demonstrate In-situ Propellant Production-- ISPP-- for the first time on Mars [3-5]. The experiment was designed to show that it was possible to produce oxygen from the carbon dioxide atmosphere, and to demonstrate the individual technology components that would go into a full-scale production plant. The aimpoint of the oxygen production was to showcase the possibility of producing oxygen for use as rocket fuel, ultimately as an enabling technology for a future human expedition to Mars. The logo for the experiment (Figure 1) shows a fuel pump, to indicate how in-situ propellant production could be used as a gas station for a future mission.

A. Background

After the highly successful Viking lander mission to Mars in 1976, Mars was neglected as a destination for robotic planetary exploration for the nearly two decades. The return to robotic planetary missions to Mars came with the Mars Pathfinder mission, which was proposed as the first of a series of small, low-cost missions in what eventually became the NASA "Discovery" mission program. The successful lander of the Pathfinder probe on July 4, 1997, twenty-one years after the Viking lander, and the deployment of the Sojourner micro-rover that it carried, generated a high degree of excitement about Mars exploration. Then NASA Administrator Daniel Goldin made a commitment to sending two

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[1] Researcher, Photovoltaic and Electrochemical Technology Branch. Associate Fellow, AIAA.

low-cost missions to Mars at each launch window (approximately every 2.2 years), to be called the Mars "Surveyor" program, consisting of both Surveyor Lander and Surveyor Orbiter spacecraft.

At about the same time that the Mars Surveyor program was being planned, David Kaplan at NASA Johnson Space Center (JSC), in collaboration with NASA Lewis (LeRC, now Glenn) Research Center, proposed to the Human Exploration Operating Plan the idea that an upcoming robotic mission to Mars should include a technology demonstration payload to demonstrate oxygen production on Mars as a way to develop the technology toward a human mission. Oxygen production had been worked on at a small scale previously, primarily by University researchers, but Kaplan believed that only an actual demonstration on Mars would serve to break through the roadblock of engineering reluctance to rely on unproven technology.

Figure 1: The mission logo for the MIP (Mars ISPP Precursor) experiment.

Surprisingly, the concept was highly rated, and an agreement between the Associate Administrator of the Science program (Code S) and the Associate Administrator for Human Spaceflight (Code M) was arranged, in which the human exploration program would share the cost of the mission in exchange for flying the HEDS (Human Exploration and Development of Space) technology demonstration payload. This became the MIP project: Mars ISPP Propellant Precursor. MIP merged Dave Kaplan's oxygen production technology demonstration with a proposal by Geoffrey Landis to test solar power generation, and eventually formed a cross-center collaboration with experiment leads from NASA Ames and NASA Jet Propulsion Laboratory as well, bringing in Gerald Sanders as overall project manager.

The first of the Mars Surveyor Lander spacecraft became the Mars Polar Lander mission, to launch in 1999; MIP was manifested to fly on the second of the series, the 2001 Surveyor Lander. The MIP experiment is shown on the 2001 Surveyor Lander spacecraft in Figure 2.

B. Selection of oxygen generation process

Propellant production, at its most basic level, requires a raw material to manufacture propellant from, and energy.

As pointed out originally by Ash [6], the most readily accessible available resource on Mars is the atmosphere. The advantage of using the atmosphere as the raw material is that the atmosphere is available at every location on the planet, and has a known composition. Carbon dioxide (CO2), which makes up more than 95% of the atmosphere, is 72.5% oxygen by weight, and thus was the primary resource being considered as feedstock for propellant production for early Mars missions.

Several different methods of producing propellant from the Martian carbon dioxide have been proposed. The Sabatier reaction process, advocated most notably by Robert Zubrin in the "Mars Direct" plan [7], proposes bringing hydrogen from Earth to reach with the carbon dioxide in the reaction

$$2H_2+CO2 \rightarrow CH_4 + 2H_2O \qquad (1)$$

which is followed by an electrolysis reaction

$$2H_2O \text{ (plus electricity)} \rightarrow H_2 + O_2 \qquad (2)$$

An advantage of this reaction is that it produces both methane fuel as well as oxygen (although for stoichiometric combustion, additional oxygen must be generated by a different process, possibly the solid-oxide electrolysis discussed below). However, the fact that hydrogen must be brought from Earth, or else gathered from Mars, makes this a much more difficult process to demonstrate on a small scale (within the 8.5 kg mass budget of the MIP experiment).

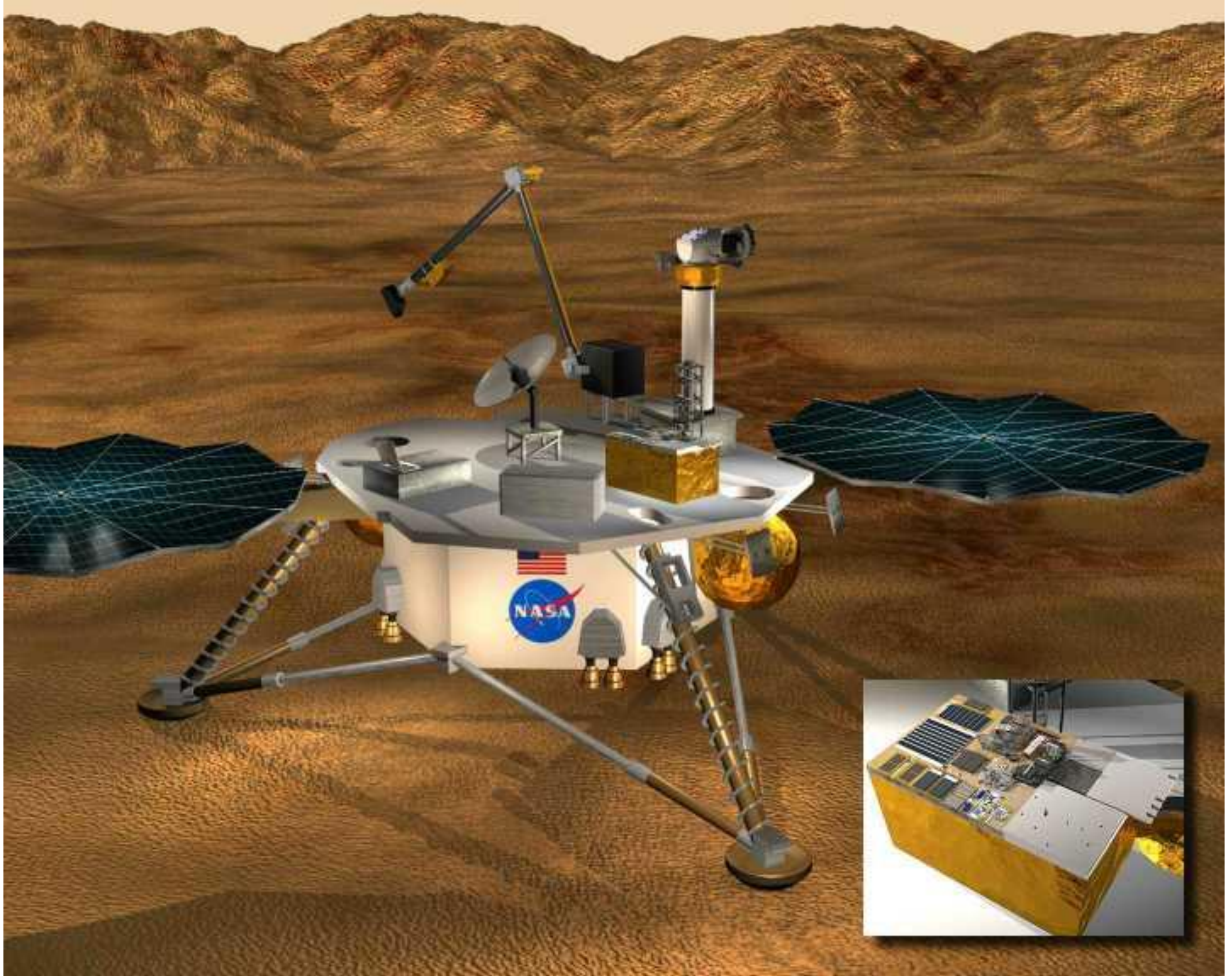

Figure 2: Conceptual rendering of the 2001 Surveyor Lander spacecraft, showing the location of the MIP experiment (covered in gold MLI thermal coating, on the top deck). The MIP experiment is shown in detail in the inset in the lower right.

Instead, a process was selected in which oxygen is generated directly from the carbon dioxide atmosphere. This is done by direct electrolysis [8]:

$$\begin{aligned}&\text{(cathode): } CO_2 + 2e^- \rightarrow O^{2-} + CO\\ &\underline{\text{(anode): } 2\ O^{2-} \rightarrow O_2^- + 4e^-}\\ &\text{(net) } 2\ CO_2 \rightarrow O_2 + 2\ CO\end{aligned} \tag{3}$$

The operation via a high-temperature (~750°C) electrolysis using a zirconia-based solid electrolyte, which is conductive to oxygen ions. As illustrated in Figure 3, an electric field drives oxygen ions across the zirconia electrolyte to produce pure O2, with CO as a byproduct. This process uses the technology developed for solid-electrolyte fuel cells, with the modification that the reactant is carbon dioxide, instead of the more commonly used water. The carbon dioxide byproduct is exhausted.

Since no reactant is brought from Earth, the process has an advantage of significant simplicity and low mass.

Due to its simplicity, the solid-oxide electrolysis of Martian carbon dioxide has been proposed to generate oxygen to fuel the ascent vehicle for a Mars Sample return [8-11], although NASA's current baseline plan for a sample return mission concepts uses propellant brought from Earth.

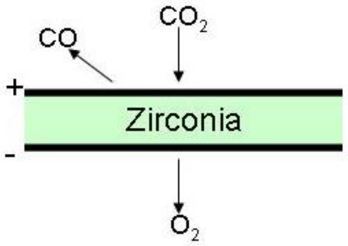

Figure 3: schematic of solid-electrolyte electrolysis.

C. MIP experiments

MIP comprised five distinct experiments, to demonstrate the key components of the in-situ propellent production:

- Mars Atmospheric Acquisition and Compression (MAAC)
- Oxygen Generator Subsystem (OGS)
- Mars Thermal Environment & Radiator Characterization (MTERC)
- Mars Array Technology Experiment (MATE)
- Dust Accumulation and Repulsion Test (DART)

II. MIP experiments

The MIP flight hardware is shown in figure 4. Its overall external envelope is approximately 40 x 24 x 25 cm (15.7 x 9.4 x 9.8 inches), about the size of a shoe box. The total mass was 8.5 kg (18.7 lb).

Components visible on the top surface are the radiator experiment (MTERC), the white and grey portions on the top left, and the solar cell and dust experiments, MATE and DART; the darker honeycomb panel on the right. The atmospheric compression and the oxygen generation units, along with the control electronics, are inside the thermal box below.

Power to operate the MIP was provided from the lander photovoltaic arrays, with a total of 25 W total power available to be partitioned among all of the payloads on the lander. Due to the solar power operation, the highest power payload, the Oxygen Generation System, was given a maximum continuous power limit of 15W, for daytime-only operation.

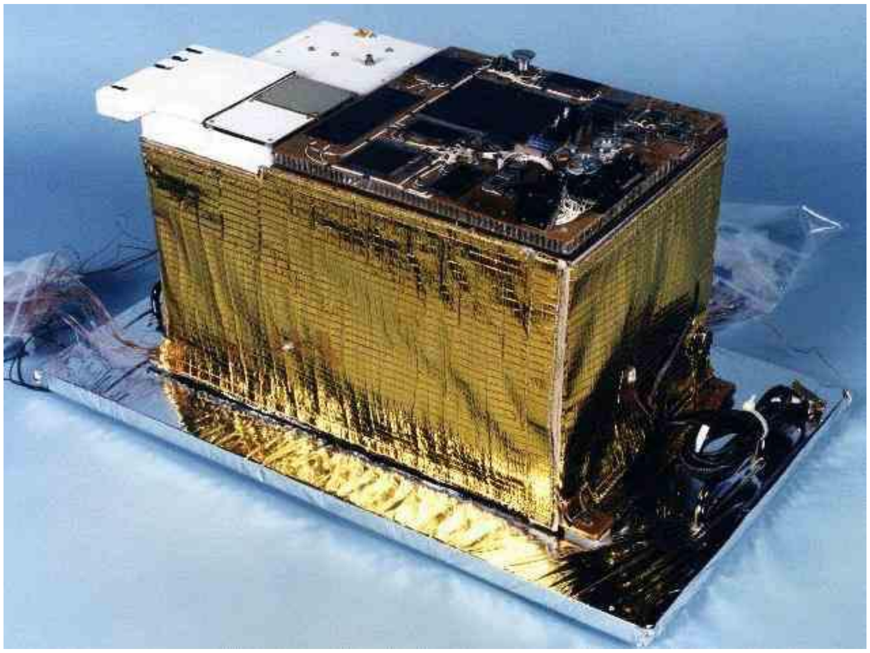

Figure 4: MIP flight hardware

A. Mars Atmospheric Acquisition and Compression (MAAC)

The Mars Atmospheric Acquisition and Compression experiment was led by co-Investigator Paul Karlmann at JPL.

Since the input to the Oxygen Generation System requires CO_2 stream at a higher density than the Martian atmosphere (700-800 Pa), a critical component of the system is to acquire and compress the atmosphere. The MAAC collected and compressed atmosphere using a carbon dioxide sorption pump [12], which selectively absorbs CO_2 from the Martian atmosphere. The sorption compressor consists of a pressure vessel filled with a zeolite that selectively absorbs carbon dioxide at low temperature During the cool night, the absorbent material is open to the Martian atmosphere and adsorbs CO2. As the temperature heats up during the day, the pressure vessel is closed, and the heated absorbent material releases the adsorbed CO2, pressurizes it, and stores it for use by the OGS. The net result is to compress the atmosphere from 800 Pa to 55 kPa using the Mars day/night thermal cycle.

B. Oxygen Generation Subsystem (OGS)

The Oxygen Generation System was designed and fabricated at the University of Arizona under contract to the NASA Johnson Space Center. The OGS co-Investigator at the University of Arizona was K. R. Sridhar, with R. Scott Baird the Project Manager at the Johnson Space Center.

OGS was designed to produce propellant-grade, pure oxygen by electrolysis of carbon dioxide from the compressed Martian atmosphere. The unit built for the MIP experiment continued the work done by K.R. Sridhar (then at the Space Technologies Laboratory at the University of Arizona) [8].

The flight unit built for the Surveyor mission (shown in Fig. 5) had a mass of 1 kg and was designed to produce 0.04 g/hr. of O_2 at 131.5mA cell current, approximately 1.6V applied voltage [15]. The electrolyzer generated higher O_2 flow rates with correspondingly higher input voltages (up to a maximum tested voltage of 2V) and CO_2 feed rates, but the output rate was limited by the power available. Since the Martian night temperature (-80°C) is much lower than the OGS operating temperature (750°C), the OGS was designed with electric heaters to increase the temperature at the beginning of each day. At 15 W input power, it took about 105 minutes to reach temperature, but required only 9.5 W steady-state power to maintain the operating temperature.

During integrated MIP testing, OGS successfully demonstrated coordinated operations with the MAAC experiment, oxygen generation from MAAC supplied CO_2, and mission length operations. OGS also demonstrated it could survive exposure to accelerations in excess of 20G during vibration testing.

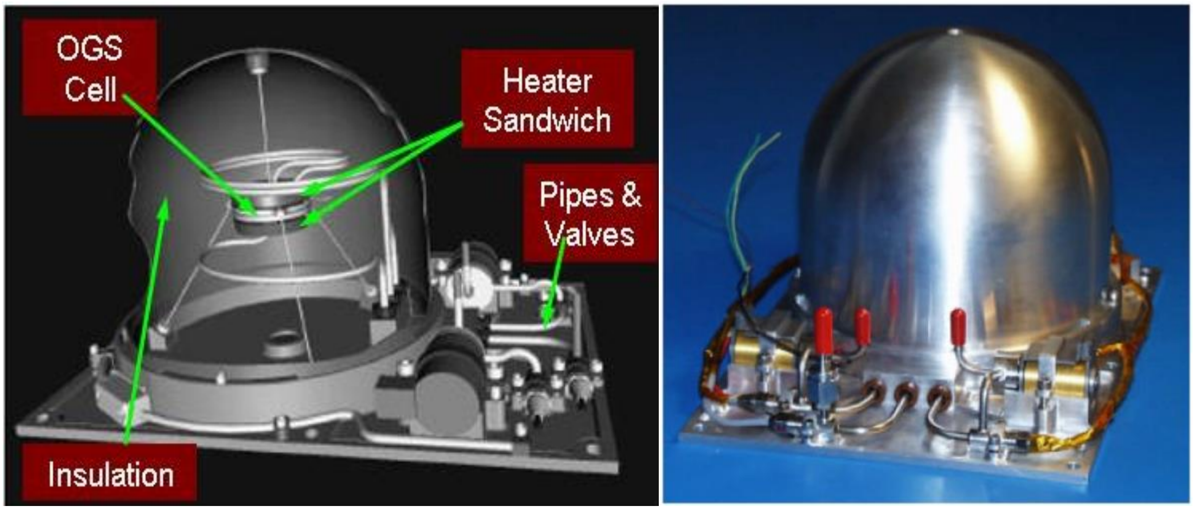

Figure 5: Oxygen Generation System (OGS) Development Unit built for the MIP experiment on the Mars-2001 Surveyor Lander experiment. Left: labelled schematic. Right: flight unit.

C. Mars Thermal Environment & Radiator Characterization (MTERC)

Co-Investigator for the MTERC was David Brinza at JPL.

Thermal management is critical for efficient operation of an ISPP plant, and waste heat is rejected to space via thermal radiators. Heat removal radiators will be required for such operations as cooling down the sorption pump sorbent bed, and cooling oxygen and fuel before liquefaction and storage. MTERC was to characterize and demonstrate the performance of thermal radiators and measure the night sky temperature [16]. The MTERC experiment included four radiator plates: two with high emissivity and two with low emissivity. One high and one low emissivity plate were protected by a movable cover to serve as the experiment control radiators, allowing the effect of dust deposition on the radiator performance to be observed.

D. Mars Array Technology Experiment (MATE)

The co-Investigator for MATE was David Scheiman at NASA Glenn.

Energy is the critical parameter for production of rocket propellant from in-situ material. At the time that the MIP experiment was planned, solar cells had not yet been operated on the surface of Mars, and even when the final flight hardware for MIP was being built, the total experience with solar cells on Mars was the 85 day duration of the Mars Pathfinder on the surface of Mars. Performance of solar arrays for the 500-sol surface stay anticipated for a Mars sample return mission incorporating ISPP was still unknown. Since making propellants and storing them cryogenically requires significant power, power genera-ion over a long period of time is critical for mission success.

The MATE experiment [17] was to test the performance of several advanced photovoltaic solar cells in the Martian solar environment, and measure the direct and scattered solar spectrum at the Mars surface. MATE incorporated five different individual solar cell types, two different solar cell strings, and temperature sensors to characterize promising solar cell materials and designs. MATE incorporated two radiometers and a dual spectrometer, to measure the global solar spectrum from 300 to 1700 nm, incorporating two separate photodiode arrays each with its own fiber optic feed and grating. Besides measuring the solar spectra on Mars, the dual spectrometer were intended quantify daily variations in spectra and intensity, and improve atmospheric modeling.

E. Dust Accumulation and Repulsion Test (DART):

The co-Investigator for DART was Geoffrey Landis at NASA Glenn.

Pathfinder data suggested that dust settling from the Martian atmosphere could be a significant factor in the degradation of solar arrays on Mars [18]. DART was to measure the dust settling rate, investigate the properties of settled dust and to test techniques to mitigate the settling of airborne dust onto solar arrays [19,20]. To measure the properties of settled dust, DART incorporated a dust accumulation monitor essentially similar to the MAE experiment on the Sojourner rover [18], and a microscope. The microscope measured the amount and the properties of settled dust, and determine 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. The DART experiment also tested various possible ways to mitigate dust deposition, including tilted solar cells, low-friction surface coatings, and high-voltage electrostatic dust repulsion. DART also carried the sun position sensor package, to calibrate the solar cell performance against sun angle for both MATE and DART.

III. The End

Fabrication and qualification testing of the MIP flight hardware was completed in 1999, and was delivered for qualification testing in preparation for integration onto the Lander in the summer of 2000.

On December 3, 1999, the first of the Mars Surveyor Lander spacecraft, the Mars Polar Lander, crashed during its landing sequence. Since the Mars 2001 Surveyor lander that was to carry the MIP experiment to Mars was an identical spacecraft, the Surveyor Lander program was put on hold. A review board of the failure of this mission, along with the Mars Climate Orbiter (which had failed a month and a half earlier) concluded that the “faster better cheaper” approach to planetary exploration had resulted in too many cuts of critical safety checks, and the Mars Surveyor Lander program was cancelled.

Following the cancellation of the Surveyor 2001 mission, the MIP Team was instructed to proceed with testing the unit and completing the completed flight hardware. From November 1999 to August 2000, a rigorous set of tests was conducted on a MIP Qualification Unit in order to demonstrate the robustness of the payload design, and the MIP Flight Unit (figure 4) was completed and placed into storage to wait for a flight [5].

The already-built spacecraft was also put into storage, and eventually (after the flaws with the landing system were identified and fixed) was resurrected, renamed the Mars “Phoenix” mission, and flew to Mars in 2007… but with a new science payload that did not include MIP.

MIP never flew to Mars, and the team dispersed to other projects.

IV. Conclusion

Although MIP ultimately never flew, the core concept of a flight demonstration of production of oxygen by solid-electrolyte electrolysis of the Martian carbon dioxide atmosphere was eventually resurrected in the form of the MOXIE package [1,21,22]. MOXIE (Mars Oxygen ISRU Experiment) is a larger, higher power, and higher flow rate oxygen demonstration unit, but nevertheless, a unit which utilizes the same underlying technology. MOXIE is now on its way to Mars on the Perseverance rover, and thus the heritage of MIP lives on. Possibly one day in the future the technology that we pioneered will be an enabling feature for a future sample return, or eventually for a human mission to Mars.

Acknowledgments

I would like to acknowledge the entire MIP team for their exceptional work in putting together an exemplary experiment package on a tight budget and a tighter schedule, and making it come in on time, on spec, and on budget.

You guys were the best.

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