Cubesat Application for Planetary Entry (CAPE) Missions: Micro-Return Capsule (MIRCA)

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ABSTRACT

The Cubesat Application for Planetary Entry Missions (CAPE) concept describes a high-performing Cubesat system which includes a propulsion module and miniaturized technologies capable of surviving atmospheric entry heating, while reliably transmitting scientific and engineering data. The Micro Return Capsule (MIRCA) is CAPE's first planetary entry probe flight prototype. Within this context, this paper briefly describes CAPE's configuration and typical operational scenario, and summarizes ongoing work on the design and basic aerodynamic characteristics of the prototype MIRCA vehicle. CAPE not only opens the door to new planetary mission capabilities, it also offers relatively low-cost opportunities especially suitable to university participation. In broad terms, CAPE consists of two main functional components: the "service module" (SM), and "CAPE's entry probe" (CEP). The SM contains the subsystems necessary to support vehicle targeting (propulsion, ACS, computer, power) and the communications capability to relay data from the CEP probe to an orbiting "mother-ship". The CEP itself carries the scientific instrumentation capable of measuring atmospheric properties (such as density, temperature, composition), and embedded engineering sensors for Entry, Descent, and Landing (EDL). The first flight of MIRCA was successfully completed on 10 October 2015 as a "piggy-back" payload onboard a NASA stratospheric balloon launched from Ft. Sumner, NM.

INTRODUCTION

So far, no microprobe (less than 10 kg) has entered another planetary atmosphere and successfully relayed data back to Earth. Although the Deep Space 2 Mars microprobes did reach their destination (total mass about 6.5 kg each), unfortunately they were lost due to a combination of delivery system failures and other unknown factors. This paper describes a planetary entry probe based on the widely popular Cubesat-class spacecraft specification (Cubesat Application for Planetary Entry Missions, or CAPE probes) [1], [2]. Within a science operational context, CAPE probes may be sent from Earth to study a celestial body's atmosphere, or to land on some high-value target on its surface. Either one or multiple probes may be targeted to distributed locations throughout the geographic landscape and could be released systematically and methodically from an orbiting spacecraft. CAPE vehicles would each have their own propulsion, and hence would be capable of targeting regions identified by the mother ship (MS) as high-interest. This enables a completely new capability for science not possible with traditional "drop-and-flyby" schemes. To supplement its flexibility, each probe would incorporate a communications architecture that provides a high-level of assurance its precious data is acquired and transmitted back to Earth for analysis.

CAPE

CAPE consists of two main functional components: the "service module" (SM), and "CAPE's entry probe" (CEP). The SM contains the subsystems necessary to support vehicle targeting (propulsion, ACS, computer, power) and the communications capability to relay data from the CEP probe to an orbiting mother-ship. The CEP itself carries the scientific instrumentation capable of measuring atmospheric properties (such as density, temperature, composition), and embedded engineering sensors for Entry, Descent, and Landing (EDL) technology monitoring and assessment. Figure 1 illustrates the complete CAPE system in its flight and stowed configurations. The total system mass is less than 5 kg. The solar array generates about 17W at 1 AU, and the SM nominally consumes less than 11W of power. The CEP itself consumes less than 5W.

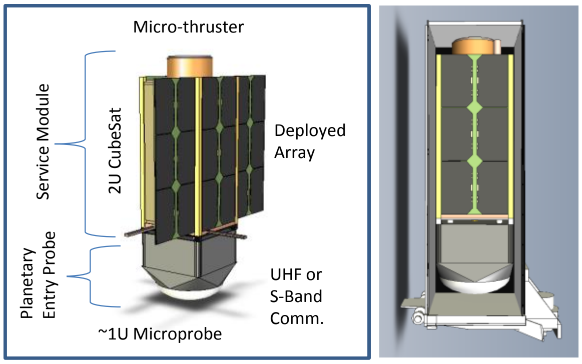

Figure 1: CAPE in its deployed configuration, and stowed inside deployment system

Figure 2 shows a generic CAPE operations concept, from system deployment to probe release and entry into a given planetary atmosphere. Other scenarios include direct entry on arrival. Three mission phases are identified: 1. Deployment, 2. Targeting, and 3. Planetary Entry. In the initial phase the vehicle rides inside a deployment system, and is released by the mother-ship in a prescribed drop-off orbit. This drop-off orbit is adjusted in a way that ensures atmospheric entry within the capabilities of CAPE's thruster system, but at a safe altitude for the mother-ship. During the targeting and orbit adjustment phase, CAPE uses its own thrusters to slowly target a particular entry corridor. Since entry dispersion is expected to be large, a "ground track" path (or great circle on the planet's surface), rather than a specific spot is targeted. The final mission phase is planetary entry. At this time, the SM is maneuvered to allow for a slightly delayed entry from the CEP. CEP to SM cross-link communications will ensure data is relayed to the orbiting MS, although direct communication to the MS is also possible (depending on orbital mechanics and view factors). Since the SM will be trailing behind the CEP, it will go through communications blackout after the probe has completed its entry phase, and hence will be capable of relaying a full set of probe scientific and engineering data. The SM will continue to relay communications until it burns up in the atmosphere.

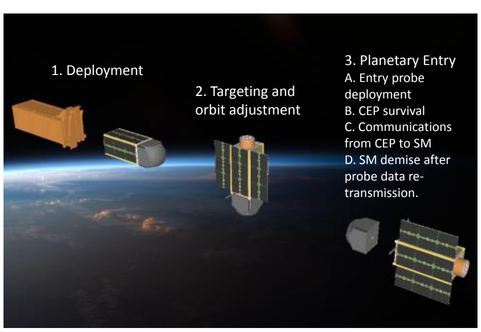

Figure 2: CAPE typical mission phases.

CAPE entry probes can provide essential insight into the bulk properties of planetary atmospheres. Sent in numbers, they render the potential to observe multiple in-situ locations in a planet or satellite's atmosphere. CAPE opens up an entirely new capability and manner of exploration for NASA, with high potential for university and student participation.

MIRCA

In order to reduce CAPE's implementation risks, a CEP re-entry demonstrator is currently being designed and prototyped at the NASA Goddard Space Flight Center (GSFC). The Micro Return Capsule (MIRCA) is CAPE's first planetary entry probe flight prototype. The primary objectives are to verify MIRCA's avionics architecture, communications and operations concept, and aerodynamic stability.

Entry probes have provided essential insight into the bulk properties of planetary atmospheres by measuring their density, temperature, and composition. Much information can be inferred from accelerometers, rate gyros, thermal and pressure sensors alone. This is exemplified by accelerometer data acquired through the experimental SMART (Small Rocket/Spacecraft Technology) spacecraft prototype, which re-entered Earth's atmosphere after launching from a sounding rocket in 2011 (Fig. 3) [3].

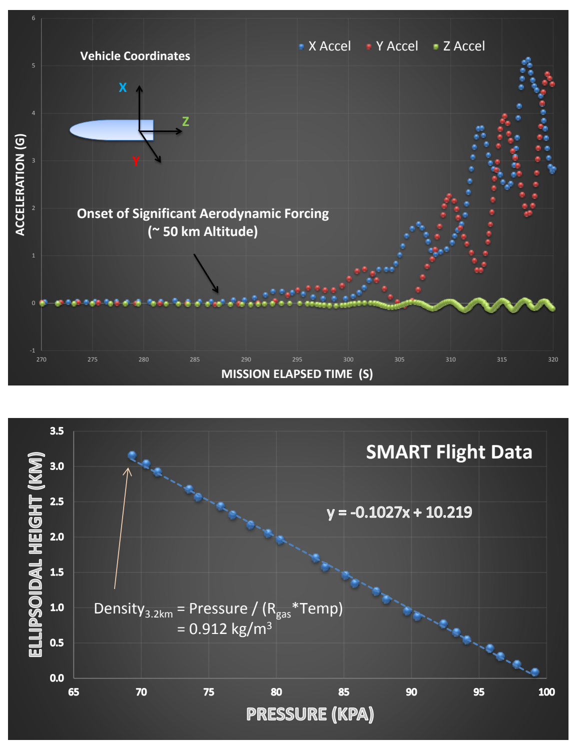

Figure 3: SMART re-entry data at 50km (top) and 3km altitude (bottom).

As can be seen, significant atmospheric forcing begins at an altitude of about 50 km (stratopause), although environmental conditions can moderately shift this interface's location. Although this result is far from surprising for Earth's atmosphere, simple and direct measurements like these can be a critical piece of information in the determination of the structure of extra-terrestrial atmospheres. Coupled with pressure and temperature sensors, a simple entry probe would provide direct confirmation of remote sensing measurements (e.g., estimation of the atmospheric gas constant and mean molecular weight). Figure 4 shows data obtained by the Huygens Atmospheric Structure Instrument (HASI), with sensing instrumentation similar to the one described in this paper [4]. Since a probe altimeter is not feasible at this time, a CEP's altitude will be modeled from its trajectory and timing signals relayed to the release (mother) ship. Alternatively, a MS may already be carrying a science Radar which could also be used to range to the entry vehicle during its flight.

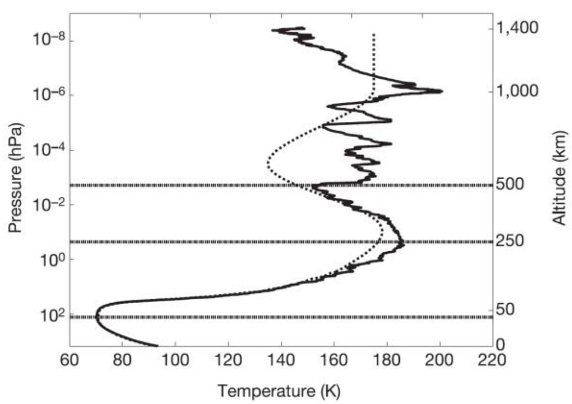

Figure 4: Titan's atmospheric structure inferred from temperature and pressure sensors (Ref. 4).

Direct sensing of acceleration, pressure, and temperature parameters is not only of importance to science, but is also critical in the engineering assessment of entry vehicles and their design. The same suite of instrumentation that provides insight into a planetary atmosphere will also measure the vehicle's aerodynamic stability during its flight path, and determine its thermal performance.

On-board radiometers can improve the capability of CEP probes, by providing in-situ gas analysis. MIRCA is testing out a simple thin-film radiometer than can be easily installed within its resource limitations. This sensor has a flat spectral response from 100nm to > 100μm, which can be tailored with wide-band optical filters, or narrow-band filters designed to measure specific gases (e.g., CH_4, CO_2, CO, HC, etc.). Tailoring would depend on the atmosphere of choice, and can include Venus, Mars, Titan, or the giant planets. For this test, a sapphire filter is used with a band pass wavelength between 0.1 and 7 μm. Center wavelength of sample gases within this band pass range is shown in Table 1 for Earth's atmosphere [5]. Gas mixing ratios and the corresponding atmospheric absorption spectra will vary depending on altitude. Hence, detection of atmospheric gas species as the vehicle descends provides invaluable information not only on atmospheric composition, but also its structure. Measurements will be tempered by heat shield ablation materials during the critical heat-loading phase of the vehicle flight. Notwithstanding, this information is also of great engineering interest, and provides a measure of TPS performance.

Table 1: Earth atmospheric gases absorption center frequencies for visible and near-IR bands.

Gas	Center Wavelength (μm)
CH4	1.66, 2.2, 3.3
CO2	1.4, 1.6, 2.0, 2.7, 4.3
CO	2.34, 4.67
H_2O	0.72, 0.82, 0.94, 1.1, 1.38, 1.87, 2.7
N_2O	2.87, 4.06, 4.5
O_3	3.3, 4.74
O_2	0.63, 0.69, 0.76, 1.06, 1.27, 1.58

Important considerations have been the demonstration of an inexpensive planetary entry probe, and assessment of its science performance, constraints and capabilities. To that effect, MIRCA has been built and is currently undergoing testing. A picture of MIRCA during bench test is shown in Fig. 5.

Within the context of CAPE probes, it is quite feasible (actually expected) that these entry vehicles will be sent in multiple quantities (tens, perhaps) at a time, so in-situ observations have the potential of having great spatial resolutions. Furthermore, the ability of CAPE to provide great-circle targeting (depending on propulsion system) makes the selection of entry time and region somewhat controllable. This is important as high, mid, and low latitudes can be targeted for in-situ analysis during the same mission (such as the atmospheres of the giant planets). Outer planets however, would require the development of small radioactive power sources (a few watts) to enable probe autonomy.

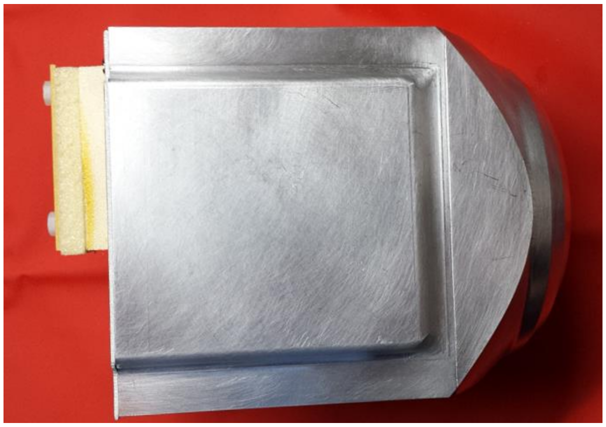

Figure 5: MIRCA, CAPE's first planetary entry flight prototype during test at NASA GSFC.

First Flight Verification

The first flight of MIRCA was successfully completed on 10 October 2015 as a "piggy-back" payload onboard a NASA stratospheric balloon launched from Ft. Sumner, New Mexico. This completed verification of its avionics, including the Inertial Measurement Unit (IMU), single board computer, power conditioning and distribution system, communications transceiver, on-board thermal sensor, telemetry acquisition system, and flight software, all critical steps in MIRCA's development. Figure 6 shows a view from 30 km altitude, as well as data from the IMU during gondola release and parachute deployment.

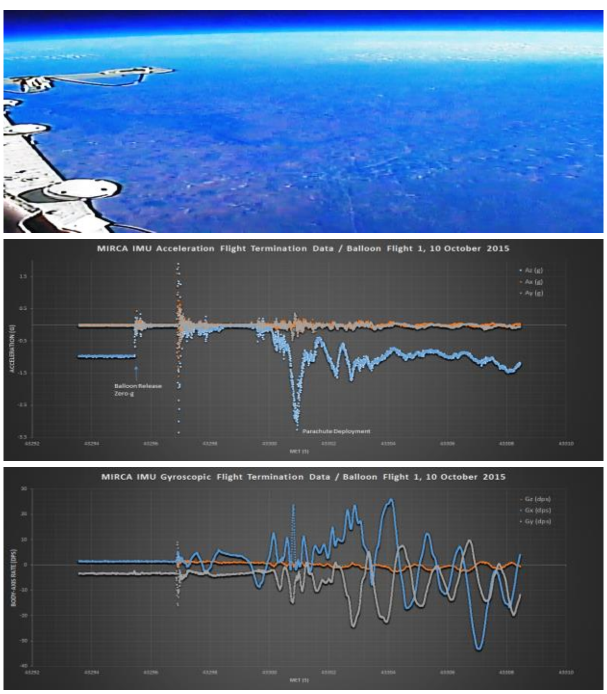

Figure 6: MIRCA flight data.

Acceleration and body rate data recreate vehicle dynamics. Maximum axial (+Z-axis vertical) deceleration was about 3.3g for this flight after parachute deployment. Cyclic vehicle swinging under parachute (X and Y axes) is also evident from the IMU data.

Balloon Drop Demonstration of MIRCA

A second flight is planned for 2016 to demonstrate vehicle release, real-world aerodynamic performance at high speed, and recovery system. Analysis of the vehicle in freefall from a starting altitude of 30 km (98,425 feet) results in a flight profile as shown in Figure 7. Computational Fluid Dynamics (CFD) analysis was performed at selected points in the trajectory. The vehicle reaches a maximum speed of ~203 m/s (Mach 0.65 or 455 mph), about 33 seconds after release at an altitude of ~20.7km (67,913 feet). The terminal velocity is about 80 m/s (179 mph) at ~6 km altitude (20,000 feet), about 144 seconds (2.4 minutes) after release.

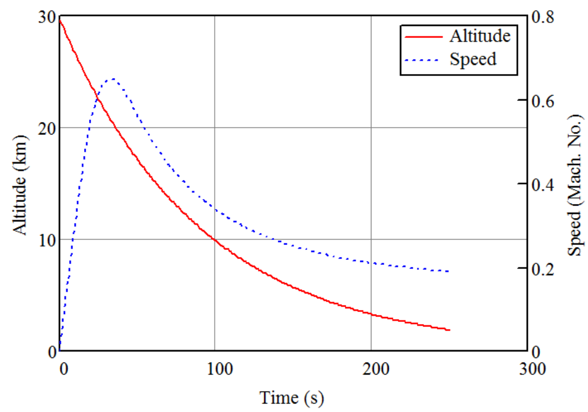

Figure 7: Calculated vehicle altitude and speed during freefall from 30km altitude.

The operations scenario for this test is shown in Figure 8. MIRCA is released from the balloon gondola at ~ 30 km altitude. Telemetry from the probe is recorded on-board and simultaneously transmitted to the gondola. Matching radios are used in both locations. An optional ground receiver may be added as well. This scenario would replicate an actual planetary mission flight concept, in which the vehicle is released from the SM (i.e., gondola in this case), and the SM re-transmits the data back to the MS (i.e., ground antenna in this case). Since direct probe-to-MS transmission is also possible, the ground receiver is considered optional pending logistic and resource allocations for this test.

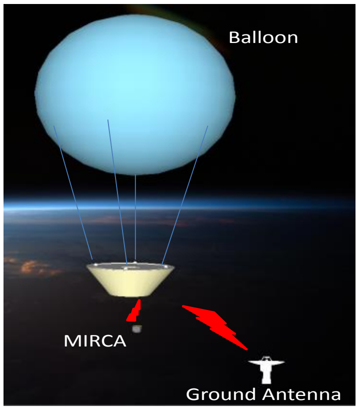

Figure 8: MIRCA is released from near space, at 30 km altitude.

Flight is expected to take place from Ft. Sumner, NM. Wind conditions are one of the main drivers in launching balloon payloads. Acceptable wind speeds at parachute deployment altitude are also desirable to prevent too much drift and aid recovery. The exact release parameters will depend on factors such as wind speed, direction, drop height, parachute deployment altitude uncertainties, release position, etc.

Flight dynamics and stability

Vehicle stability is critical in at least two aspects: the ability to survive entry into a planet or satellite's atmosphere at hyperbolic velocities, and the ability to communicate to the SM and/or MS. Typical aero-shell configurations are either conical, or of sphere-cone design. MIRCA is unique in that it follows a *sphere-truncated-cone square* (SCS) design. This design was initially motivated to fit within the Cubesat specification standards.

Analysis and verification of vehicle aerodynamic stability has been one of the main topics of research, and successful validation will depend on results from the balloon drop experiment. MIRCA weights about ~1.5 kg, and has a cross-sectional area of about 100 cm^2. Equipment arrangement is such as to locate the Center of Mass (CM) as far forward of the Center of Pressure (CP) as possible. Static and dynamic stability conditions have been *verified* via analysis, but *validation* requires an actual flight (especially the behavior at high speeds). High-speed wind tunnel data would provide valuable information, but it would not simulate release and dynamic effects, nor would it allow for real-life communications validation. Computational Fluid Dynamics (CFD) analysis using 3-dimensional compressible Navier-Stokes equations was carried out at different altitudes and Angles of Attack (AOA). Boundary conditions were obtained at maximum speed. Documenting all the different calculations and variations are out of scope for this paper. However, key results are summarized.

Figure 9 shows surface pressure and temperature results at maximum speed. Stagnation point pressure is ~ 1.3 atm. Maximum temperature is ~ 55° C, and average body temperature ~ 42° C.

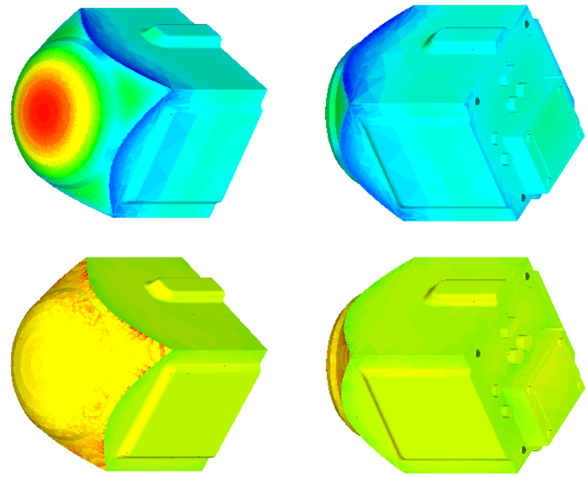

Figure 9: CFD results at maximum speed and zero angle-of-attack (top, pressure; bottom, temp.).

Static stability conditions require that there be a restoring moment about the CM, as the vehicle strays away from a stable zero AOA attitude. Figure 10 shows a plot of the pitching moment coefficient as a function of angle of attack. An increasingly large (negative value) restoring moment about the CM points to static stability, with ~ 0.2 N-m at AOA = 20°. Restoring moment magnitude increases considerably with increase AOA, being ~0.45 N-m (4.0 lb-in) at 45°. Although static stability is satisfied, there may be some concern resulting from initial tip-off rates (vehicle is release with no spin).

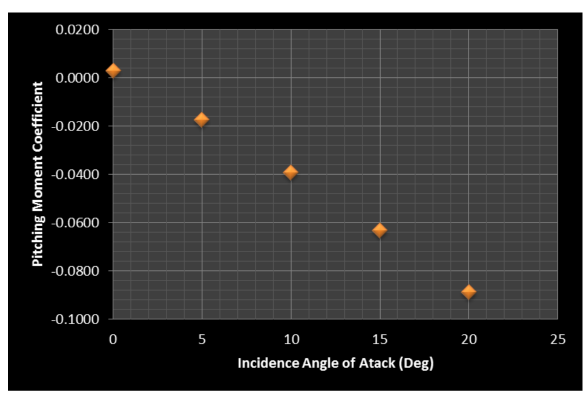

Figure 10: Static stability condition is satisfied for MIRCA

Dynamic instabilities resulting from deployment can be such that the vehicle attitude on entry results in a large AOA. Given hyperbolic entry speeds, a large AOA on entry can translate into significant aerodynamic heating over parts of the vehicle not designed to survive high heat loads. Gyroscopic stability on release is essential in those cases.

Figure 11 shows MIRCA inside a wind tunnel at the NASA Wallops Flight Facility (WFF), where laminar flow and aerodynamic stability were demonstrated at low speeds. The test was also used to validate corresponding CFD results.

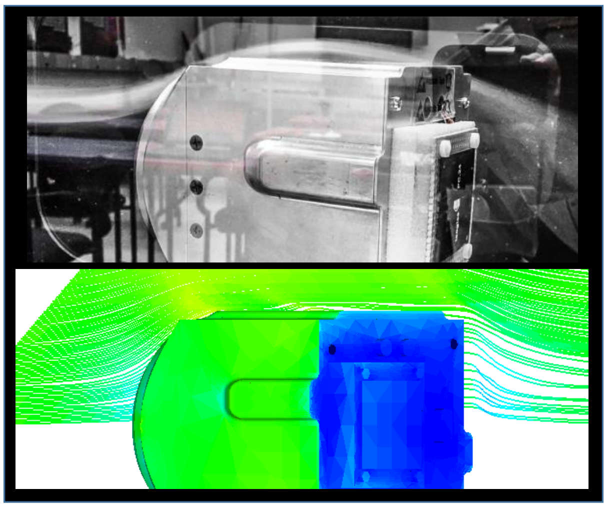

Figure 11: MIRCA in wind tunnel test at NASA WFF (shown at angle of attack ≈ 20°).

LOW EARTH ORBIT (LEO) RE-ENTRY DEMONSTRATION

In order to continue to develop the concept, and to reduce the risks associated with a scientific mission, plans to further the development of CAPE/MIRCA through a test campaign that involves Earth re-entry are ongoing. One possibility is to launch MIRCA in one of NASA's CubeSat Launch Initiative (CSLI) flights to the International Space Station (ISS), or alternative opportunities.

Development and test of a new TPS material is one of the key aspects of this demonstration. One candidate material (albeit not exclusive) is the Resin Impregnated Carbon Ablator (RICA), which showed promise in plasma wind tunnel testing carried out in 2010 [6].

Thermal Protection System Material

Ablative materials are required to protect a space vehicle from the extreme temperatures encountered during the most demanding (hyperbolic) atmospheric entry velocities, either for probes launched toward other celestial bodies, or coming back to Earth from deep space missions. To that effect, RICA is a high-temperature carbon/phenolic ablative thermal protection system (TPS) material designed to use modern and commercially viable components in its manufacture. Heritage carbon/phenolic ablators intended for this use rely on materials that are no longer in production (i.e., Galileo, Pioneer Venus); hence the development of alternatives such as RICA is necessary for future NASA planetary entry and Earth re-entry missions. RICA's capabilities were initially measured in air for Earth re-entry applications, where it was exposed to a heat flux of 14 MW/m^2 for 22 seconds. Methane tests were also carried out for potential application in Saturn's moon Titan, with a nominal heat flux of 1.4 MW/m^2 for up to 478 seconds. Three slightly different material formulations and six samples were manufactured and subsequently tested at the Plasma Wind Tunnel of the University of Stuttgart in Germany (PWK1) in the summer and fall of 2010. The TPS' integrity was well preserved in most cases, and results show great promise (Figure 12).

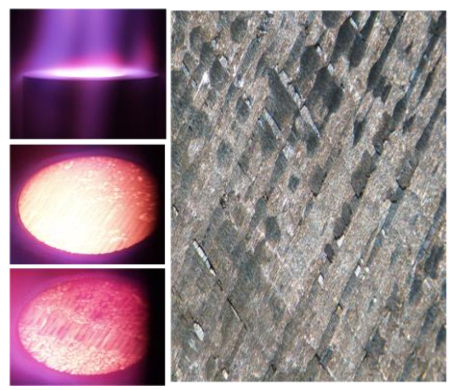

Figure 12: RICA Samples were tested at the PWK1 plasma wind tunnel (shown during and after test).

There are several major elements involved in the creation of a successful ablative TPS material: the choice of fabric and resin formulation is only the beginning. The actual processing involved in manufacturing involves a careful choice of temperature, pressure, and time. This manufacturing process must result in a material that survives heat loads with no de-lamination or spallation. Several techniques have been developed to achieve this robustness. Variants of RICA's material showed no delamination or spallation at intended heat flux levels, and their potential thermal protection capability was demonstrated. Three resin formulations were tested in two separate samples each manufactured under slightly different conditions. A total of six samples were eventually chosen for test at the PWK1. Material performance properties and results for five of those are shown in Table 2.

In the most extreme case, the temperature dropped from ≈3,000 to 50 °C across 1.8 cm, demonstrating the material's effectiveness in protecting a spacecraft's structure from the searing heat of entry. With a manufacturing process that can be easily re-created, RICA has proven to be a viable choice for high speed hyperbolic entry trajectories, both in methane (Titan) as well as in air (Earth) atmospheres. Further assessment and characterization of spallation and an exact determination of its onset heat flux (if present for intended applications) still remain to be measured. Applications for other atmospheres (such as Mars or Venus) is also possible.

Table 2: RICA Properties and initial test results.

ID	Phenolic ~%	Carbon ~%	Density (gm/mL)	Heat Flux (MW/m^2)	Heat time (s)	Integrated Heat Input (J/m^2)	Mass Loss (gm)	Average Recession (mm)	Average Surface Temp from Pyrometer (C)	Average Thermal Gradient (K/mm)	Heat of Ablation (J/kg)
5C	17	83	1.41	1.4	478	6.69E+08	7.84	4.218	1978.1	44.37	4.9E+07
5A (1)	27	73	1.39	14	22	3.08E+08	3.33	1.96	3336.1	34.32	1.1E+08
3A	24	76	1.36	1.4	478	6.69E+08	3.32	0.342	1962.5	54.50	8.5E+07
5B	33	67	1.37	1.4	476	6.67E+08	3.73	1.217	1990.8	53.68	7.7E+07
3B	31	69	1.35	1.4	477	6.67E+08	3.70	1.143	1967.5	51.11	8.5E+07
(1) Tested in Air; all others tested in Methane atmosphere (Titan)											

POTENTIAL APPLICATIONS: MARS AND PHOBOS

CAPE has potential application is many planetary in-situ measurements, from the atmospheres of outer planets and satellites, to Mars and Venus. Analysis for each of the applications is out of scope for this paper. However, a possible scenario involving launch from LEO into Mars and Phobos is provided, as an example (Figure 13).

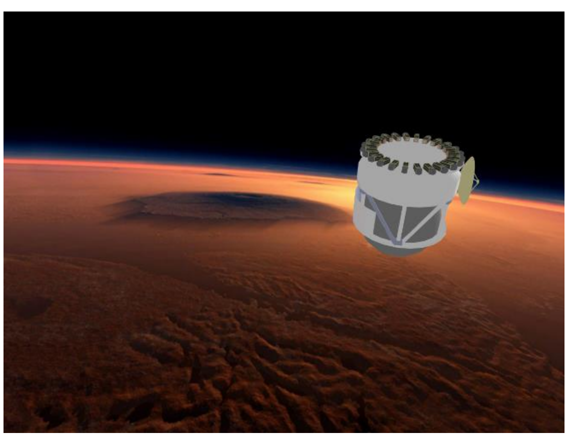

Figure 13: CAPE vehicles on board a carrier spacecraft approaching Mars.

The assumption is that a constellation of CAPE Cubesats are injected into Mars from a "carrier" vehicle deployed from the ISS at 400 km altitude. Chemical propulsion is used, but solar electric propulsion is also possible (with much longer flight times). A similar scenario is just as likely for a dedicated launch and injection from a 180 km parking orbit. The following assumptions are made in reference to the injection vehicle and payload: Launch Date to coincide with arrival at the 13 October 2020 Mars opposition [7]; Cubesat Mass = 4.5 kg each; Mars Injection Stage (from ISS orbit) with solid motor, I_{sp} = 280 secs.; Carrier Spacecraft with Liquid Monopropellant, I_{sp} = 290 secs. Results are summarized in Table 3.

Table 3: Flight and Sizing Data for a CAPE Mission to Mars/Phobos

Flight Data		Launch 2020
Departure Orbit Altitude		400 km
C3		8.7 km^2/s^2
Departure Date ~		1/1/2020
Flight Time		0.71 years
Arrival Date at Mars ~		10/13/2020
Departure ΔV		3.6 km/s
Mars Orbit Insertion ΔV		1.05 km/s
Delta V to Phobos Orbit		0.83 km/s
No. Cubesats to Phobos	**Departure Mass From ISS (kg)**	**Arrival Mass at Phobos (kg)**
1	717	80
2	764	85
3	810	90
4	857	96
5	903	101
6	950	106
10	1135	127

Trajectory optimization and staging can be carried out. For instance, a number of Cubesats can be made to enter Mars on arrival, and others can be carried on to study Phobos and/or Mars from Phobos orbit. The next synodic period opportunity for Mars after 2020 would be 8 December 2022, with a corresponding departure date from the ISS of about 23 March, 2022.

SUMMARY AND CONCLUSIONS

CAPE represents an entirely new and pioneering paradigm in planetary exploration, using the advantages and standardization common to Cubestas. MIRCA is clearing the way by systematically reducing the technological and operational risks associated with the application of this new paradigm to planetary exploration.

Acknowledgements

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