MONTGOLFIERE AEROBOTS FOR TITAN

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ABSTRACT

Montgolfieres, commonly known as "hot air balloons," are balloons that are filled with heated ambient atmospheric gas. These balloons appear very promising for large-scale scientific exploration of the atmosphere and surface of Saturn's moon, Titan. Titan was once geologically and chemically very similar to the early warm Earth when life first appeared, although Titan became literally frozen in time. Analysis at JPL has shown that a double-hull Montgolfiere heated by a radioisotope power source (RPS) could travel safely with the winds at 10 km altitude and could make numerous circumnavigations of the Moon during a multi-month mission.

Altitude control of small unmanned Montgolfieres has been demonstrated on Earth and has shown that Montgolfieres can be controlled to take numerous surface samples for scientific analysis. Mission lifetimes lasting many years may be possible, since the RPS power source has a half-life of about 88 years, and turbulent weather is extremely rare. Also, small leaks do not impair performance of ambient-gas-filled Montgolfieres. The primary scientific goal of this type of mission would be to look for evidence of ancient biotic or prebiotic activity in the atmosphere or in the frozen surface water ice.

1. INTRODUCTION

Montgolfieres, which are balloons that are filled with heated ambient atmospheric gas, were first flown over two centuries ago by the Montgolfier brothers in France. The original Montgolfiere used burning wool to heat air inside a balloon, while present commercial hot air balloons more commonly use burning propane. Other types of Montgolfieres that have flown on Earth include solar-heated Montgolfieres and radiant-heated Montgolfieres.

Since the 1970s, the French Centre National d'Etudes Spatiales (CNES) has flown over forty Montgolfieres in the Earth's upper stratosphere, which is similar to the Martian atmosphere, for periods of up to 69 days [1]. The Montgolfieres were generally 40-m diameter or larger and fabricated from 12-micron (0.0005-in.) Mylar and polyethylene. Heated by the Sun during the day, they rose to an altitude in the stratosphere corresponding to about 10 mbar pressure. At night, the Montgolfieres were warmed by radiant Earth heat and descended to an elevation with a pressure of about 40 mbar.

Since Montgolfieres are relatively impervious to small leaks and since the stratosphere is generally a very benign environment, the primary failure mechanism after successful deployment has been the occasional presence of high-altitude cold clouds at nights. This has caused the balloons to lose buoyancy and descend to Earth.

2. MARS MONTGOLFIERES

The Jet Propulsion Laboratory (JPL) has been involved in the testing of solar-heated Montgolfieres for Mars since 1997. These balloons could potentially be used as lightweight parachutes to more gently land small payloads on Mars, or they could be used for multi-month missions during the polar summers (Fig. 1), which are about 6 months long. JPL deployed many dozens of low altitude 3–5 meter diameter solar Montgolfieres during 1997–1998. These balloons had a small opening at the bottom of the balloon that allowed them to fill while falling. All balloons that had a means to hold the bottom hole open were successfully deployed (Fig. 2). Stratospheric deployment soon followed, in order to simulate the deployment in Mars' cold thin atmosphere. Although most of the thin Mylar balloons failed due to ripping, three out of four thin, polyethylene balloons (10- to 15-m diameter) survived deployment. The fourth polyethylene Montgolfiere failed to open due to the fact that it was top-heavy, and the top fell below the bottom before the balloon could fill. The deployment of larger polyethylene Montgolfieres (as large as 30-m diameter) has met with mixed results, and further testing is underway in a joint program between JPL, NASA Wallops Flight Facility (WFF), and GSSL, a private balloon-development

company in Tillamook, Oregon. The first joint deployment of a 20-m Montgolfiere at 36 km altitude ((230 K, 0.006 bar pressure) was successful for the first minute of operation, but it failed when the separated parachute later collided with the slowing Montgolfiere (December 2005). Gliding parachutes are planned for future flights in order to avoid future collisions.

Fig. 1. The Mars Montgolfiere can be used to perform science from various altitudes, to soft-land payloads, or to take surface samples.

It should be mentioned that all large stratospheric Montgolfiere deployments are using very thin (10 micron) polyethylene balloon envelopes since heavier Montgolfieres would not float in Mars' thin atmosphere (220 K, 0.006 bar). The materials that have been developed and tested for balloon applications on Titan are over 100 times stronger, since Titan's atmosphere is about 400 times as dense as Mars, and thus stronger and heavier composite materials can be used.

3. TITAN MONTGOLFIERES

Various aerial vehicle missions to Saturn's moon, Titan, have been envisioned which take advantage of Titan's thick nitrogen atmosphere (1.46 bar, 93 K, more than four times as dense as the atmosphere on Earth). One of the simplest altitude-controlled atmospheric missions for Titan is that of a radioisotope power source (RPS)-heated Montgolfiere. For this mission, the RPS would be held inside the lower portion of the balloon, thus allowing nearly all of the waste heat to warm the internal ambient nitrogen atmosphere (Fig. 3, [2]).

Altitude control could be maintained by opening and closing a vent at the top of the balloon. Just as commercial hot air Montgolfieres can hover close to the ground (Fig. 4), so have our unmanned altitude-controlled solar Montgolfieres (Fig. 5). Altitude control of RPS-heated Montgolfieres on Titan can allow cruising with the Titan winds at 10 km altitude, as well as allow numerous samplings of water ice or methane lakes on the surface.

(a) Preparing to deploy

(b) Fully deployed from hot air balloon

Fig. 2. Deployment of solar Montgolfiere from a commercial hot-air Montgolfiere

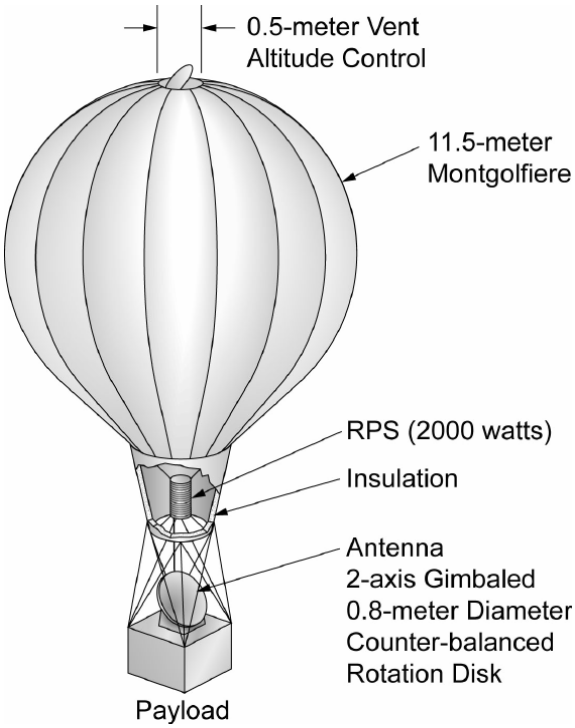

Fig. 3. Titan RPS Montgolfiere with altitude control

Fig. 4. Commercial hot air Montgolfiere descending and hovering over Lake Tahoe, California

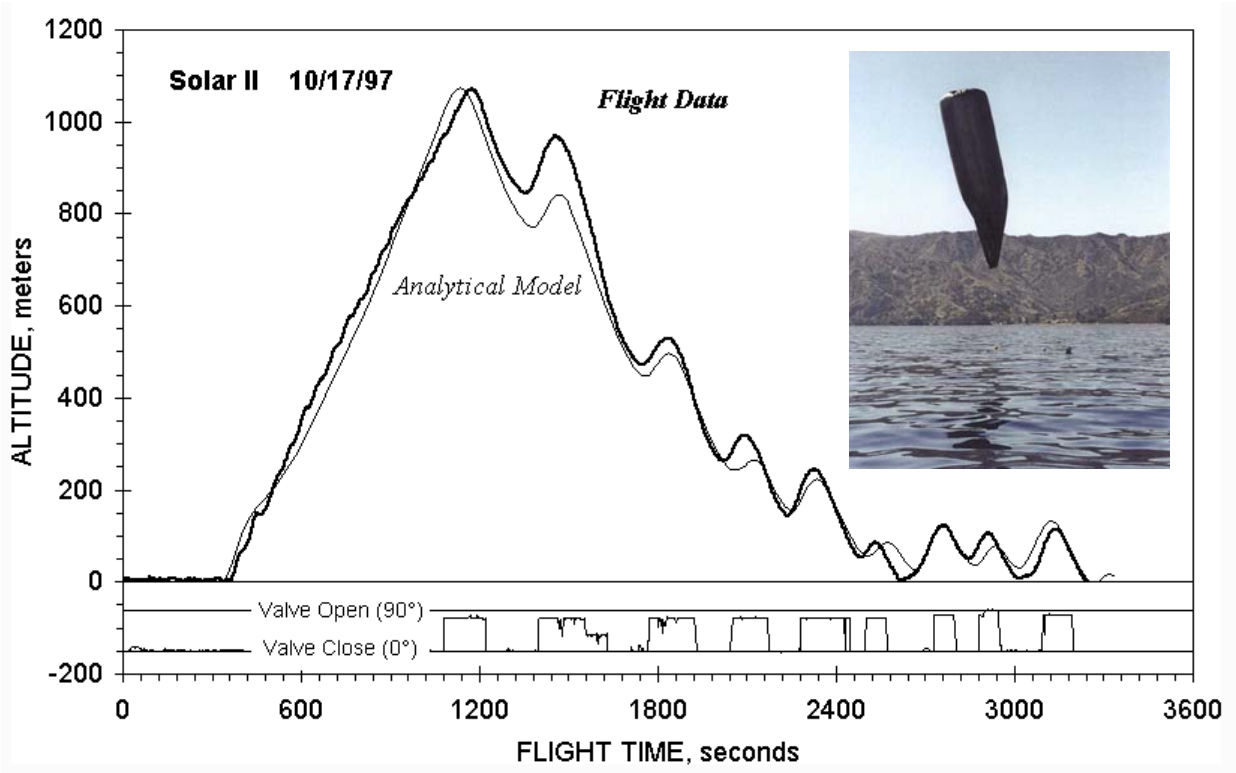

Fig. 5. The solar Montgolfiere can also hover over water. The performance closely matches thermal analyses.

3.1. Thermal Analysis

A number of thermal analyses have been performed to determine the expected performance of RPS-heated Montgolfieres in the Titan atmosphere. As discussed in [2], cold Titan Montgolfieres require only about 1% of the heat required by warmer Earth Montgolfieres. This is due to a combination of reduced cryogenic radiation, reduced convection heat transfer, and buoyancy inversely proportional to the square of absolute temperature. Two independent thermal modeling techniques, using Engineer Equation Solver (EES) and Computational Fluid Dynamics (CFD) have confirmed this with remarkably similar results. Furthermore, the EES thermal analysis [3] has been confirmed with actual test measurements of Earth solar Montgolfieres.

From simple Archimedes principles, an 11-m diameter Montgolfiere is required to float a 160-kg payload at 10 km altitude on Titan, assuming an envelope aerial density of 100 gm/m^2. The first transient analyses performed were to determine the transient heating of the Montgolfiere as it descended. It was found that 2000 W was insufficient to allow time for the Montgolfiere to heat up before hitting the Titan surface. The diameter was then increased somewhat, and the Montgolfiere was seen to almost have enough time to heat up before hitting the surface (Fig. 6). When the diameter was increased a bit more, the Montgolfiere could heat up before reaching 10 km altitude, and it could actually attain a ceiling of about 18 km (Fig. 7), well above the planned 10-km ceiling, which is safely below the Titan methane ice clouds. With the upper vent valve partially open, the balloon could descend to near the surface and maintain an altitude of about 100 $\pm$20 m (Fig. 8). The large bobbing effect is due to the rapidly changing external convection heat transfer coefficient that varies significantly with relative velocity.

In order to minimize the bobbing effect, a double-walled Montgolfiere was analyzed next. Double-walled balloons have been used in various competition balloons, such as Rozier balloons, which are a combination of helium and hot air, as well as in Aerostar double-walled competition Montgolfieres (Fig. 9). The planned double-walled design for the Titan Montgolfiere consists of an inner porous wall, surrounded by a ballooning outer wall (Fig. 10). The middle gap acts as an insulation layer to minimize heat leaks as well as to minimize effects of large changes in the external heat transfer coefficient.

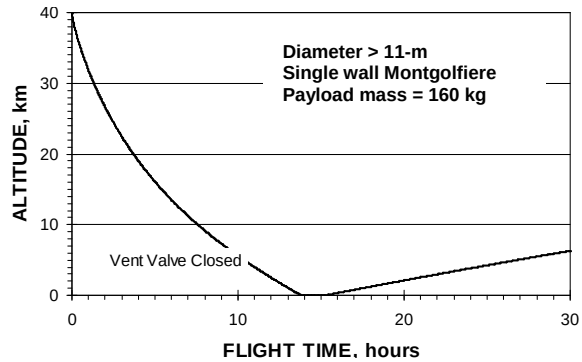

Fig. 6. Montgolfieres tend to require significant time to heat up on Titan. Smaller diameter Montgolfieres may require sitting on the surface for hours before they can lift off. This can be avoided by increasing the size of the Montgolfiere.

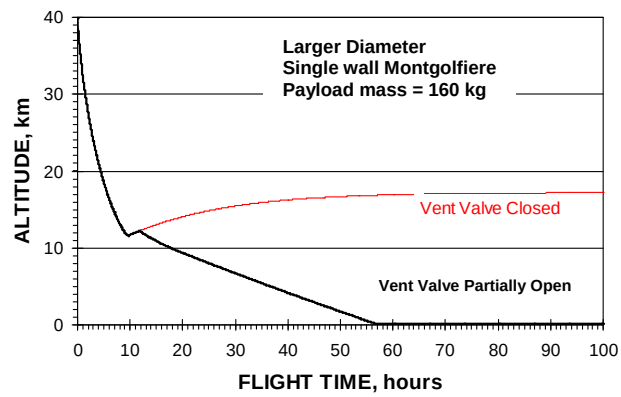

Fig. 7. Larger diameter Montgolfieres can obtain positive buoyancy before they hit the ground and maximum altitude is higher, unless the upper vent is open.

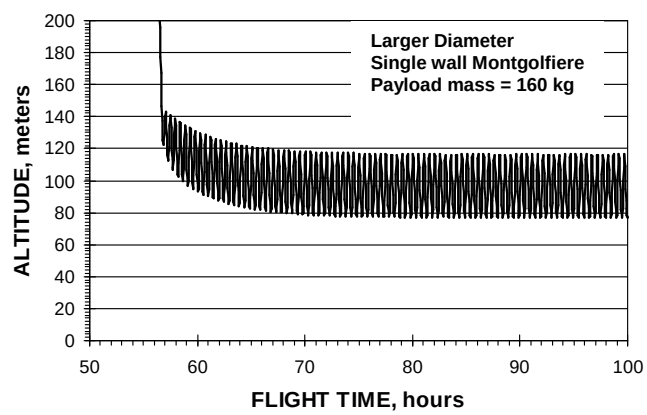

Fig. 8. This larger diameter Montgolfiere can be held to 100-m altitude $\pm$20-m, and it requires constant corrections that are a function of both altitude and velocity.

(a) Rozier balloons

(b) Aerostar International competition Montgolfieres

Fig. 9. Examples of double-walled balloons

Use of a small-gap, double hull increased the maximum ceiling of a larger Montgolfiere from 18 km to about 27 km, even accounting for a heavier total balloon envelope of 150 gm/m^2. Double-walled Montgolfieres were also found to be capable of holding much greater altitude control within ±2 m for 100-m altitude control (Fig. 12). To determine obstacle collision avoidance capability, a double-walled larger Montgolfiere analytically closed its upper vent when neutrally buoyant, and the balloon ascended at a rate of about 1 km/hr (Fig. 13). With a maximum anticipated surface wind of 1 m/sec, this corresponds to a 15º climb angle, which is considered to be quite safe, considering Titan's generally very flat surface.

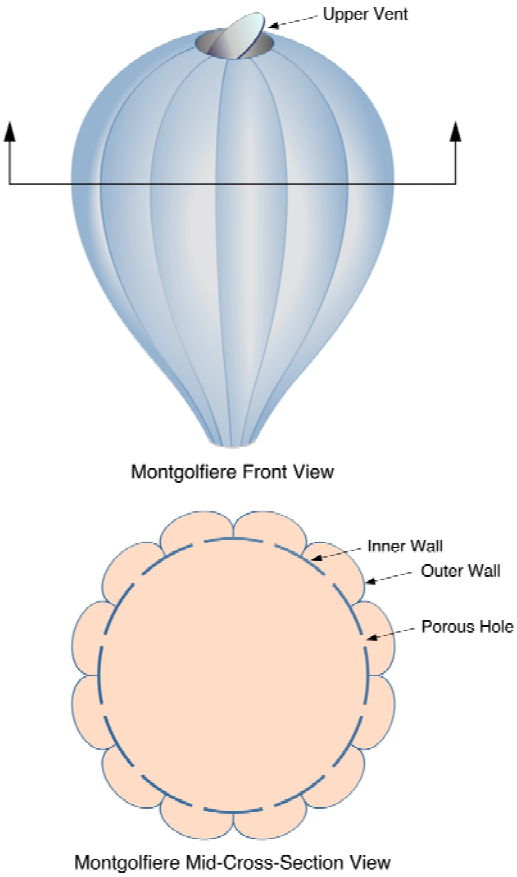

Fig. 10. The double wall of the Titan RPS-heated Montgolfiere would be similar to the Aerostar design and would have an inner porous balloon, surrounded by a larger diameter balloon, which keeps an insulating gas layer in between.

3.2. Mission Scenario

A preliminary schematic of a possible entry vehicle configuration is shown in Fig. 14. The pliable Montgolfiere envelope would be tucked to two sides in the entry vehicle to allow for last-minute placement of the RPS inside the entry vehicle prior to launch. The system would contain at least two parachutes, supersonic and subsonic, and all RPS heat rejection during cruise would be out the back lid of the entry vehicle, similar to Mars Science Laboratory (MSL).

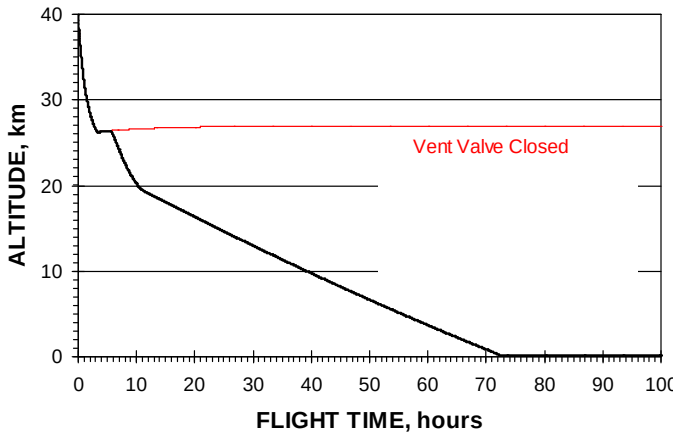

Fig. 11. An insulated, or double-walled, Montgolfiere heats up much faster and can attain much higher altitudes if the upper vent is fully closed.

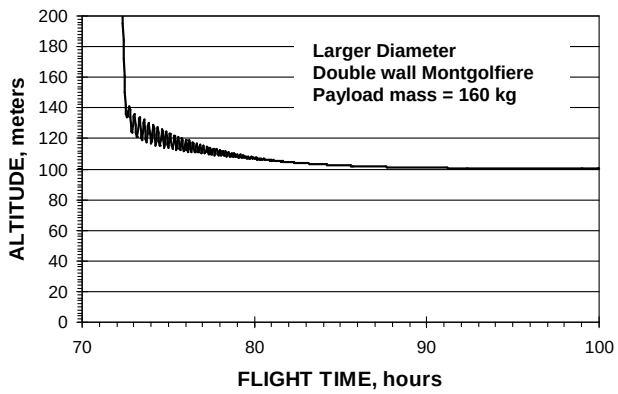

Fig. 12. The double-walled Montgolfiere can obtain a much more stable altitude, since its temperature and buoyancy are much less affected by vertical motion.

Figure 15 shows a possible deployment scenario, based on the Huygens entry. After entering the atmosphere, a supersonic pilot chute is deployed. Then a subsonic chute is deployed, followed by dropping of the heat shield. The Montgolfiere then deploys while falling under the parachute, similar to JPL's numerous Mars-simulation Montgolfiere deployments. After filling and stabilizing, the Montgolfiere descends to about 100-m altitude, which allows tethered sampling of the frozen ice surface (Fig. 16). The vehicle may be able to take advantage of anticipated reverse directional winds at lower altitude so that it can retrace its path to an area of interest seen while cruising at 10-km altitude.

Floating lifetimes are anticipated to be many years, since small leaks do not impair performance. Leaking gas is rapidly replaced and heated at the bottom of the balloon. Furthermore, turbulent weather is extremely rare on Titan, and is likely predictable. Ample RPS heating should last many decades, since the half-life of the RPS power source is about 88 years.

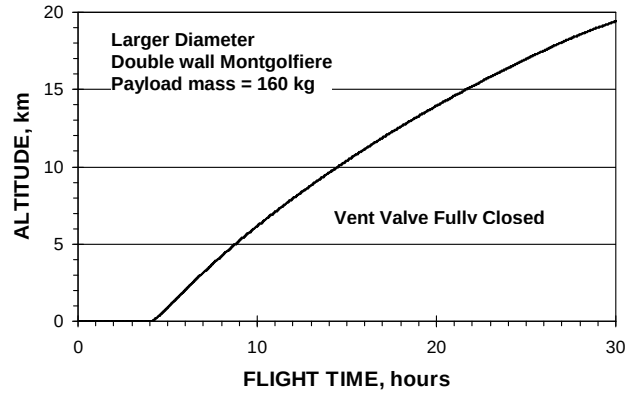

Fig. 13. If the upper vent valve is fully closed, it takes about 1 hour to climb to 1000-m altitude. With a surface wind of 1 m/sec, this corresponds to a 15º climb angle. For a descending balloon, the allowable safe descent rate has been calculated to be at least 1 km/hr.

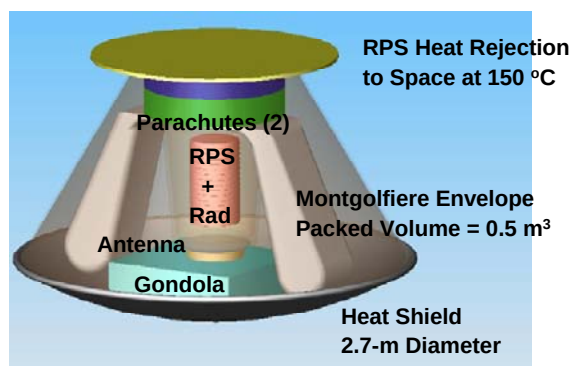

Fig. 14. The Montgolfiere envelope would be tucked to two sides to allow for last-minute placement of the RPS inside the entry vehicle prior to launch.

Titan was at one time geologically and chemically very similar to the early warm Earth when life first appeared. Both had warm liquid water oceans and thick nitrogen/methane atmospheres. Life on Earth changed the methane portion of the atmosphere to oxygen and carbon dioxide, but Titan cooled quickly and became literally frozen in time. The primary scientific goal of this global aerobat mission is to look for evidence of ancient biotic or pre-biotic activity in the atmosphere and in the frozen surface water ice of Titan. The aerobot is also expected to use wind currents to reach specific scientifically intriguing areas, such as the recent Cassini-discovered active volcano (possible present biotic activity) and the apparent liquid methane lake near the south pole.

4. FUTURE PLANS

JPL is presently developing and testing various sample acquisition and handling devices that can be used on a balloon platform, such as on the Titan Montgolfiere Aerobot. We are also developing test plans to perform thermal verification testing of double-hulled Montgolfieres in a cryogenic nitrogen atmosphere. Other development activities may include refinement of present cryogenic Montgolfiere envelope materials and testing of balloon-borne directional communications systems to confirm the ability to communicate directly from the Titan Montgolfiere to Earth.

5. REFERENCES

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6. ACKNOWLEDGMENTS

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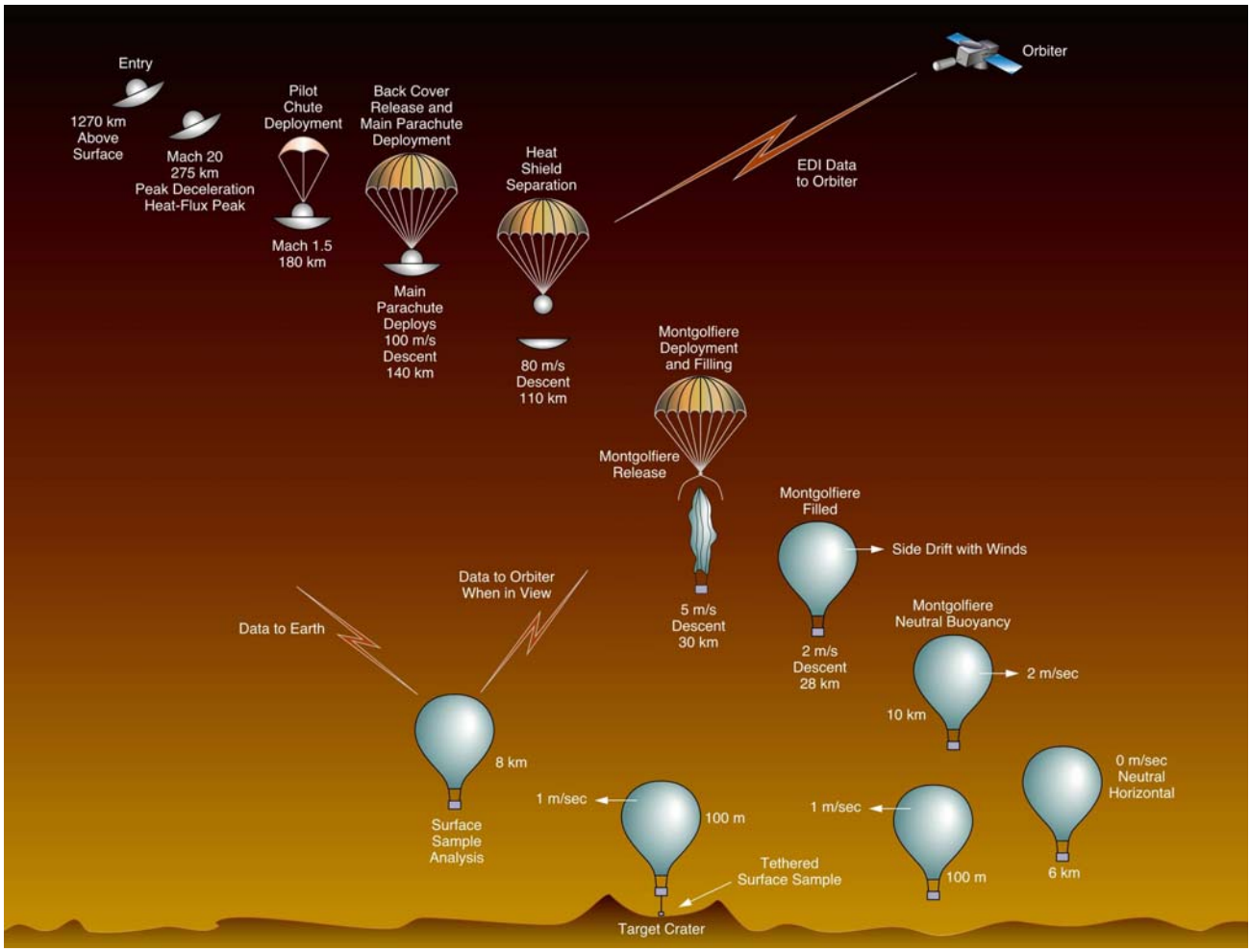

Figure 15. Titan Montgolfiere entry, descent, and inflation (EDI) scenario [4]

Fig. 16. A tethered sampling device will be used to acquire ten samples (1-2 grams each) of surface ice from 100-m altitude above the Titan surface. The samples will be pulled back up to the gondola for scientific analyses.