AERIAL MOBILITY SYSTEMS

DESIGNING, SIZING AND TESTING OF PLANETARY BALLOONS

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Outline

- Background
  - Historical snapshot, motivation, destinations,
- Balloon Design Basics
  - Types of balloons, sizing, auxiliary systems, examples
- Testing Challenges and Technology Status
- Future Possibilities / Conclusions
- References

Background

Introduction

- Balloons have been used at the Earth for two centuries for a wide variety of scientific, military, commercial and recreational purposes.

Scientific balloon launch

Goodyear blimp

Hot air recreational balloons

Weather balloon

First manned balloon circumnavigation

Planetary Balloons: VEGA

- Only two balloons have ever flown at another planet: the Soviet VEGA mission in 1985.
- Two identical copies flew for 2 days each, carried as secondary payloads on the VEGA 1 and VEGA 2 landers.
- Metrics:
  - Type: helium-filled spherical superpressure
  - 3.5 m diameter
  - Teflon-like coated fabric material
  - 7 kg payload
    - Temperature, pressure, illumination, aerosol and wind measurements
  - 53-55 km altitude (in the clouds)
  - Ambient temperature ~30 °C
  - Aerially deployed and inflated
  - Battery-powered
    - Balloons still flying when batteries died

VEGA prototype test

Motivation for Future Planetary Balloons

1. Aerial Mobility can enable robotic science observations not possible or not economical with other observation platforms
   - In situ atmospheric location
   - Aerial reconnaisance of the surface
   - Wide area coverage of atmosphere and surface (1000s of km)
   - Potentially long duration coverage (weeks or months)
2. Balloons (buoyant vehicles) do not require power to generate lift
   - This is a crucial advantage as long as electrical energy is highly constrained on space missions
   - Some buoyant vehicles (e.g., blimps) do combine buoyancy with propulsion for lateral trajectory control
     - This is arguably a more effective use of scarce electrical power for long duration missions, but comes at the price of less maneuverability versus airplanes and helicopters.

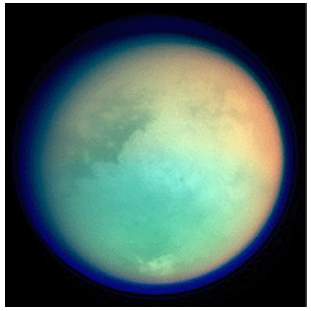
Destinations and Environments

- The vast majority of interest in planetary balloons has been on the three rocky worlds with significant atmospheres: Venus, Mars and Titan
  - Concepts for the gas giant planets are another story. . . .
- Each of these worlds has an environmental challenge that precludes simple adaptation of terrestrial technology:
  - Venus:
    - Upper atmosphere (55 km like VEGA) has benign temperatures but sulfuric acid clouds.
    - Lower atmosphere is very hot (460 °C at the surface)
  - Mars:
    - Low atmospheric density (~1% of Earth)
  - Titan:
    - Cryogenically cold temperature (85 – 95 K)
- Inherent to all of these destinations is the need to send the balloon in a folded, un-inflated condition and then deploy and inflated upon arrival.

Venus

Mars

Titan



Balloon Design Basics

Buoyancy

- Balloon design starts with consideration of buoyancy
  - How to generate it?
  - How much is needed?
  - How to modulate it (if at all).
- The fundamental equation dates to Archimedes:

$$B = V(\rho_a - \rho_g) \qquad (1)$$

where B = net buoyancy (kg)
V = volume of the balloon
ρ_a = density of the atmosphere
ρ_g = density of the gas in the balloon

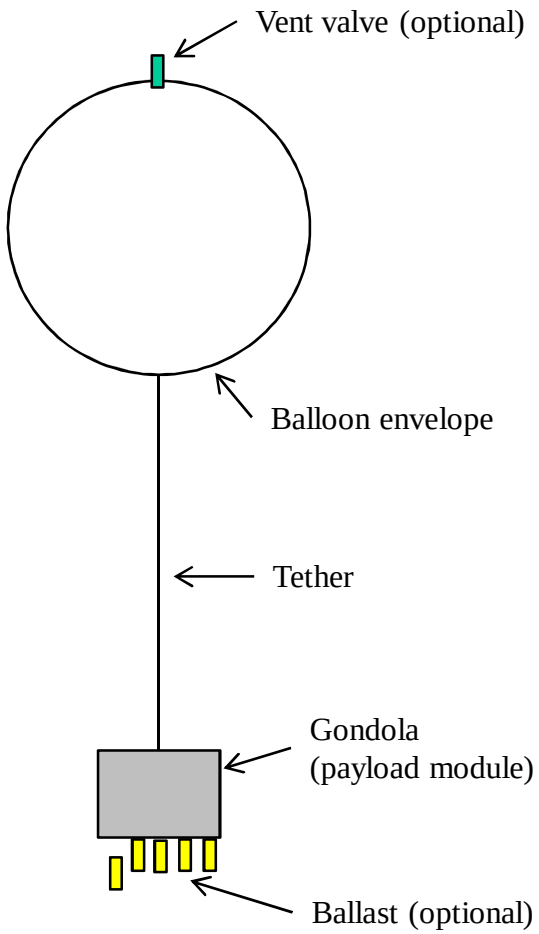
- There are two ways to make $\rho_g < \rho_a$:
  - Light Gas Balloon
    - Use a different gas than the atmosphere, one with a lower density (molecular weight)
    - Typically helium or hydrogen
  - Hot air (Montgolfiere) Balloon
    - Use atmospheric gas, but heat it up so that it has a lower density
    - The heat source can be chemical (e.g., propane burner), solar or nuclear
  - Both types can be used together (Rozier balloon)

Helium balloon prior to launch

Hot air (propane) balloon

Floating Components

- Balloon
  - "Envelope" is the usual term to describe the material that forms the gas enclosure.
  - Made from flat panels of material ("gores") that are attached to make 3-dimensional shapes.
- Gondola
  - Ranges from a wicker basket that people ride in to a complex scientific payload.
- Tether
  - A rope connecting the balloon and gondola.
- Vent valve
  - Optional component located on top of the balloon for buoyancy modulation or overpressure relief.
- Ballast
  - Optional component dropped off at intervals for buoyancy modulation.
- Heat source
  - Provides buoyancy on hot air or Rozier balloons.



Basic Sizing Calculation

- Under equilibrium conditions, the balloon buoyancy (Eq. 1) must equal the floating mass of all components (except the buoyancy gas itself).

$$B = M_{tot} \qquad (2)$$

$$M_{tot} = M_{envelope} + M_{gondola} + M_{tether} + M_{valve} + M_{heat} + M_{ballast} \qquad (3)$$

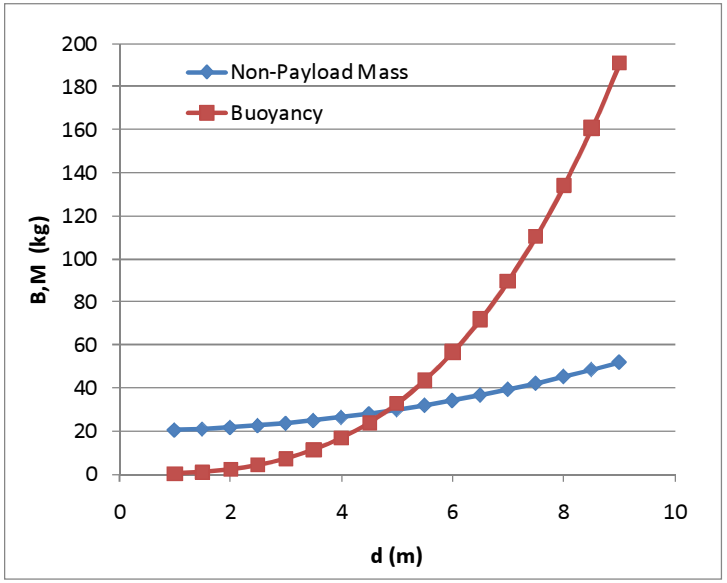
- It generally leads to an iterative calculation because both the buoyancy and envelope mass depend on the size of the balloon:

$$B \sim V \sim d^3$$

$$M_{envelope} \sim d^2$$

- The d^3 vs d^2 relationship leads to this kind of mass sizing behavior:

- There is a minimum size where the balloon is just big enough to lift itself (5m in the example at right).
- Larger balloons have a much better payload mass fraction
  - This is why so many balloons are so large!



Altitude Stability and Control

- All atmospheres are dynamic environments:
  - Temperature changes with time and altitude
  - Mean wind variations and turbulence
  - Changing solar heating (diurnal cycles)
  - Time dependent clouds
- The balloon must respond to these perturbations in such a way as to remain flying at a useful altitude.
  - If stable, the balloon will passively return to the equilibrium altitude after a disturbance.
  - If unstable, the balloon requires some form of active control to return to the equilibrium altitude, or at least to keep from crashing or bursting.
- This stability and control consideration has led to the development of a small number of standard balloon types that behave in well-understood ways (see next slide).
- Some missions require altitude excursions upon command.
  - This requires an unstable or neutrally stable balloon coupled with a control system.

Standard Balloon Types

Type	Description	Altitude Control
Superpressure	Sealed, constant volume balloon. Balloon changes pressure instead of volume. (e.g. VEGA)	Inherently stable in altitude until pressurization is lost.
Zero pressure	Vented balloon through long ducts. Most common scientific balloon used on Earth.	Requires active control. Typically achieved with gas venting and ballast drops.
Weather	Highly flexible rubber balloon, designed for one vertical profile only.	Unstable in altitude. Performs one ascent, then bursts upon reaching max altitude.
Hot air	Vented through hole at bottom of balloon. Heat source (chemical, sun, nuclear) provides buoyancy.	Requires active control of buoyancy through opening and closing of apex valve and/or burner variations for chemical heat sources.
Blimp	Sealed, streamlined, constant volume balloon. Internal compartment (ballonet) fills/unfills with ambient atmosphere to maintain internal pressure and hence shape.	Requires active control via onboard propulsion system and control surfaces (like an airplane).

What Kind of Balloon Do I Want?

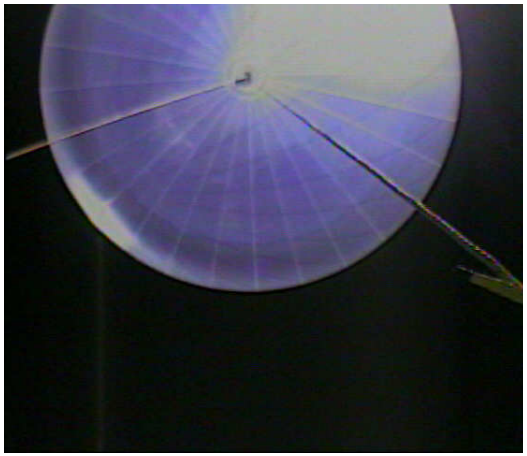
- The mission objectives will inform the choice (of course)
  - But often more than one kind of balloon can get the job done.
- Here are some typical driving considerations:
  - Ballast drops and gas venting are finite resources
    - If you need long duration flight (weeks, months) then don't pick a zero pressure balloon.
      - Exception! Long flights are possible over polar regions that are continuously illuminated by the sun with their reduced diurnal influences.
  - Conversely, superpressure balloons are great for long duration flight
    - On Earth they have flown unattended for 2+ years!
    - But you have to be willing to give up altitude changes (except at mission end)
  - Hot air balloons are a great way to have long life <u>and</u> full altitude control
    - . . . as long as you use solar or nuclear heat energy (inexhaustible)
  - A blimp will give you control over the vehicle's trajectory (has propulsion)
    - But power scarcity will limit ability to overcome the prevailing winds
    - Highly autonomous flight system is required (no teleoperation at planetary distances)

Examples of Proposed New Planetary Balloons

Venus

5.5 m diameter helium spherical superpressure balloon.

- Designed for 1 month flight duration at a 55.5 km altitude.
- Payload capacity = 45 kg.
- Teflon + Mylar + Vectran laminate material.



Mars

12 m diameter helium spherical superpressure balloon.

- Designed for 1 week flight duration at a 5 km altitude.
- Payload capacity = 5 kg.
- Mylar film material.

Titan

10.5 m diameter hot air (Montgolfiere) balloon

- Designed for 6-12 month flight duration at an 8 km altitude.
- Payload capacity = 150 kg.
- Polyester film + fabric laminate material.

Titan

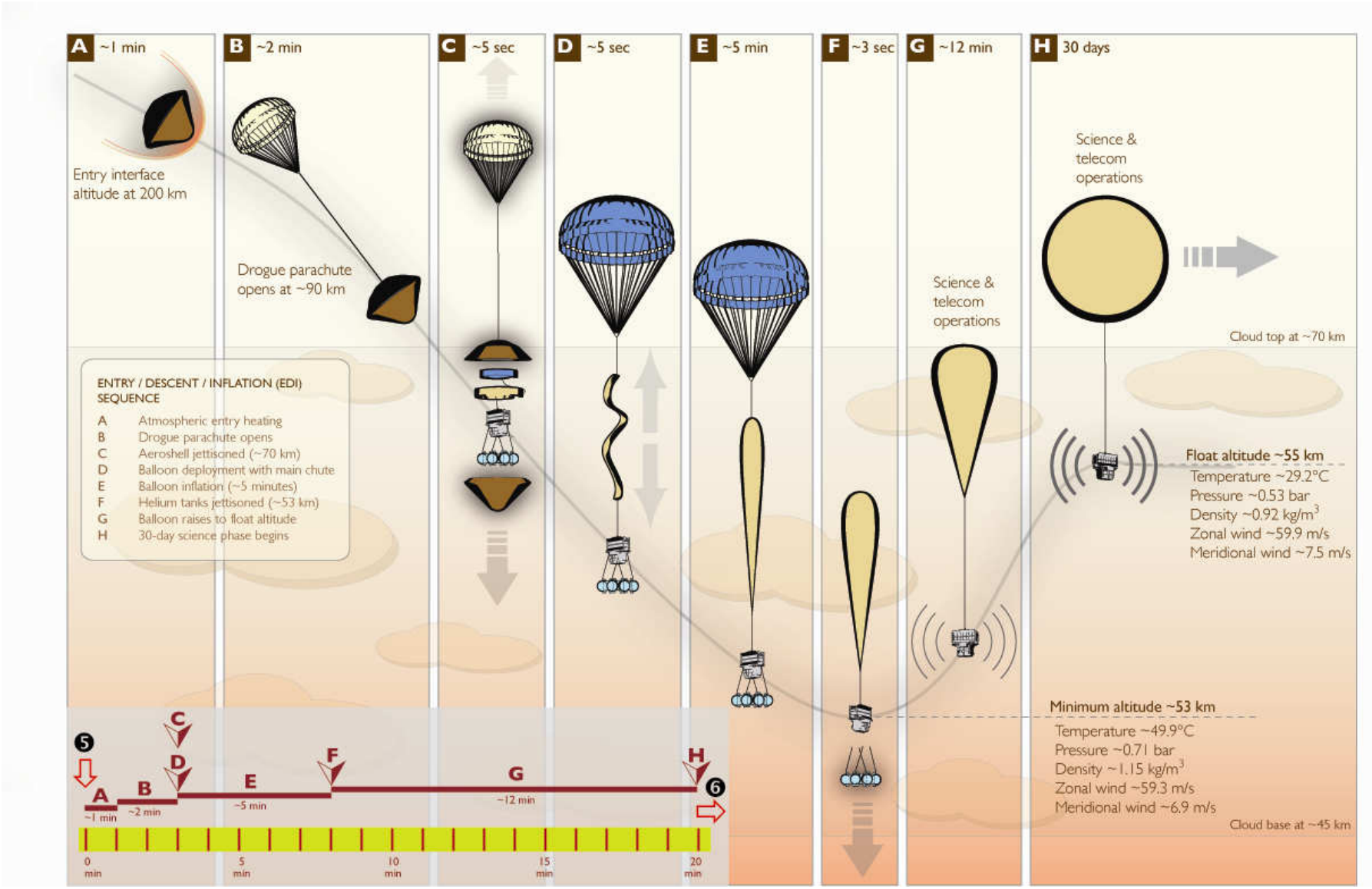
4.6 m diameter helium superpressure balloon

- Designed for 3-6 month flight duration at an 8 km altitude.
- Payload capacity = 170 kg.
- Polyester film + fabric laminate material.

Auxiliary Systems

- There are two important auxiliary systems that don't float with the balloon
  - Storage system
    - Simply a container to hold the folded balloon during transit
  - Deployment, inflation and cutaway system
    - Gas tanks, valves, tubes/pipes, actuators/cutters
- The deployment, inflation and cutaway system is the equipment and process by which the balloon goes from its folded state inside the container to floating freely in the planetary atmosphere.
  - On Earth, teams of people do this step, carefully handling the balloon at each step of the process to avoid unintended damage .
  - This process must be autonomous for a planetary balloon.
  - There are 2 basic choices:
    - Land first and deploy the balloon from the lander.
    - Deploy and inflate during the initial parachute-slowed descent through the atmosphere
  - VEGA used aerial deployment and inflation and most (all?) proposals to date have assumed the same approach to avoid the complexity and danger of landing first.
    - Note also that for Venus the surface environment is a major thermal challenge (460 °C)

Example Aerial Deployment and Inflation Sequence (Venus)



Testing Challenges and Technology Status

Verification and Validation (V&V)

- Any new terrestrial or planetary balloon requires V&V in four main technical areas to confirm suitability for a flight mission:
  - Thermodynamic behavior
    - Heat transfer performance determines buoyancy generation for hot air balloons.
    - Heat transfer with environment (incl. solar heating) determines superpressure or gas venting and ballast drop requirements.
  - Balloon envelope performance
    - Verify manufacturability
    - Ability to tolerate structural loads under flight conditions
    - Quantify leakage rate (diffusion, pinholes) for light gas balloons.
    - Environmental compatibility: temperature, chemical resistance
    - Verify flight mass
  - Deployment and inflation
    - Verify successful end-to-end operation without damaging the balloon or payload
    - Verify flight mass of support hardware
  - Storage
    - Folding and storage for required duration without damaging the balloon.
    - Verify safe packing density (volume requirement)

Ground Testing Overview

Area	Utility	Good for. . . .	Issues/Challenges
Thermodynamics	Limited	Can do static, steady-state heating conditions.	Cannot replicate free-flight aerodynamic conditions. Non-room temperature environments require specialized chambers. Full scale balloons tend to be very large, can be impractical to test at very low and very high temperatures.
Balloon envelope	Substantial	Laboratory testing of material coupons for mechanical properties. Can replicate pressure and weight loads quite well. Can measure leakage performance over long periods.	Very large facilities are required to leakage test full scale balloons for many applications.
Deployment and inflation	Limited	Laboratory drop testing can provide limited validation of structure for tolerating the deployment loads.	Aerodynamic loading is a major factor that cannot be well mimicked in ground testing. Earth analog flight environment only available for some destinations.
Storage	Substantial	This is a static phenomenon well-suited to ground testing.	Highest fidelity is achieved if the storage container is subjected to a vacuum environment similar to what is experienced during interplanetary flight.

Flight Testing

- The Earth's atmosphere provides the opportunity to flight test balloons prior to use on a space mission.
- It is crucial to pick an altitude that provides a reasonable analog environment:
  - Venus:
    - A VEGA-like altitude of 55 km (ρ = 0.92 kg/m^3, T = 29 °C) corresponds to flight in the Earth's troposphere at a 3 km altitude (ρ = 0.92 kg/m^3, T = -3 °C).
    - A near-surface Venus altitude of 5 km (ρ = 50 kg/m^3, T = 425 °C) has no good Earth analog.
  - Mars:
    - A Mars altitude of 3 km (ρ = 0.012 kg/m^3, T = -34 °C) corresponds to flight in the Earth's stratosphere at an altitude of 32 km (ρ = 0.012 kg/m^3, T = -45 °C)
  - Titan:
    - A Titan altitude of 8 km (ρ = 3.9 kg/m^3, T = 85 K) has no good Earth analog.
- Note that a balloon floating in an environmental chamber at very high or very low temperature is still "flying".
  - The chief limitation is that it can't replicate the aerodynamic loading for an aerial deployment and inflation test.

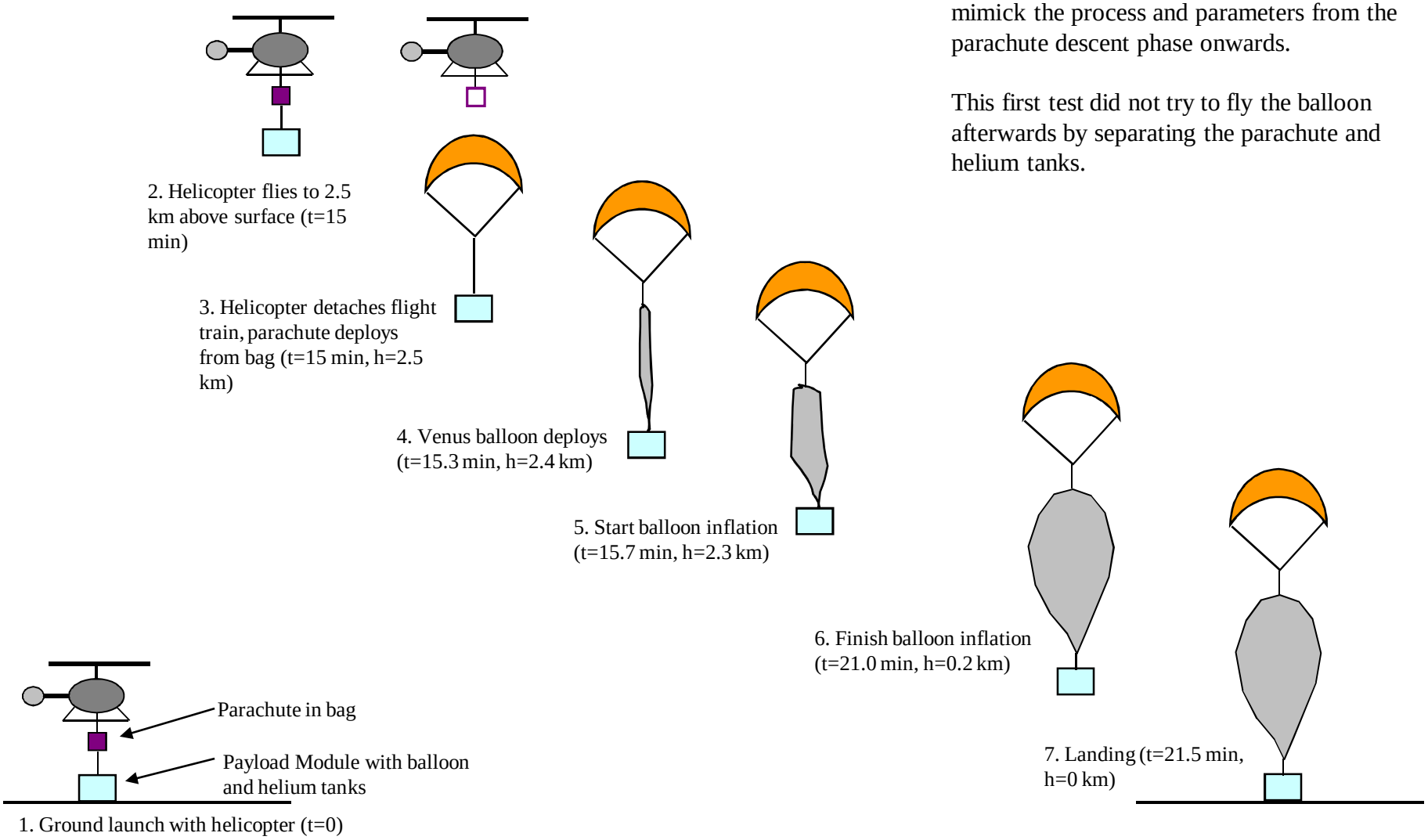
Technology Status: Venus

- VEGA balloon can in principle be re-created.
  - But it is limited to a ~7 kg payload. Material strength does not scale to larger sizes.
- Substantial development work has been done on a new Venus balloon for the same 55 km altitude as VEGA but for payloads ranging from 40 to 120 kg.
  - Current TRL is 5+
- Two 5.5 m diameter prototypes have been constructed and tested:
  - Balloon material characterized for mechanical, optical and chemical resistance properties.
  - Long duration (30 day) laboratory tests for buoyancy and leakage performance.
  - Successful aerial deployment and inflation flight test experiment.
- This balloon has been used in a Discovery mission proposal called "VALOR" and was included in the 2008 Venus Flagship Study

Flight Test Example:
Venus balloon aerial deployment and inflation

The flight test experiment was intended to mimick the process and parameters from the parachute descent phase onwards.

This first test did not try to fly the balloon afterwards by separating the parachute and helium tanks.



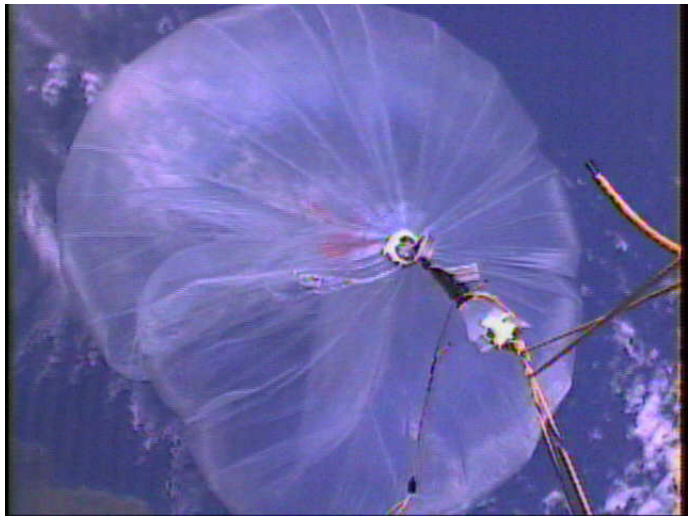
Movie

Technology Status: Titan

- Both hot air and light gas balloons have been developed in recent years for Titan.
  - Hot air concept uses waste heat from an RTG
- JPL material development program yielded polyester film+fabric laminate suitable for cryogenic operation.
- Manufacturing prototypes built:
  - 9 m diameter double-walled hot air balloon
  - 13 m long blimp
- Substantial effort devoted to the modeling and simulation of hot air balloon heat transfer.
- Substantial development and flight testing of autonomy technology (flight control, navigation, planning, etc.) for blimp vehicles.
- A hot air balloon was incorporated into the 2008 TSSM Flagship mission study
- A helium spherical superpressure balloon was incorporated into the 2011 TAE proposal to the ESA Cosmic Visions solicitation.

Technology Status: Mars

- Both Montoglifere (hot air) and light gas balloons have been developed and tested for Mars.
  - Hot air concept based on solar heating.
  - Light gas superpressure balloons based on thin polyester films, very similar to Earth balloons flown since the 1960s.
- The key challenge has been aerial deployment and inflation
  - Low atmospheric density requires lightweight (fragile) balloon material that does not easily tolerate the transient loads of deployment and inflation.
- Many prototypes built and flight tested in the stratosphere
  - Results were a mixture of success and failure, problem not solved yet for either light gas or hot air balloons.
- Helium superpressure balloon was incorporated into the 2002 Piccard proposal to Mars Scout
- Solar Montgolfiere balloon was incorporated into the 2002 Polar proposal to Mars Scout



Future Possibilities / Conclusions

- Although no planetary balloon mission has been attempted since VEGA, there has been ample demand
  - 3 Venus proposals to Discovery, 2 to Cosmic Visions
  - 1 Mars proposal to Discovery and 3 Mars proposals to Scout
  - 1 Titan proposal to Flagship, 1 Titan proposal to Cosmic Visions
  - Both the Russians and Japanese have publically discussed doing Venus balloon missions.
  - The 2011 NASA Decadal Survey includes a balloon in the alternate Venus Climate Observer flagship mission.
- Some balloon missions are (arguably) sufficient mature (TRL 5/6) for flight:
  - Venus superpressure balloon at VEGA-like 55 km altitude
  - Titan superpressure or hot air balloon flying at constant altitude (~ 8 km)

Future Possibilities / Conclusions (cont.)

- Other balloon missions require varying levels of technology development to reach that level of maturity:
  - Mars balloons must demonstrate aerial deployment and inflation.
  - More ambitious Titan balloons with altitude and/or lateral control capability require development of autonomy technology.
  - Venus low atmosphere balloons require high temperature (likely metal) balloons.
- None of these more adventurous balloon missions have issues with the underlying physics of the application.
  - The need is to solve the engineering problems and demonstrate acceptable technical risk prior to mission commitment.
- There is ongoing work at JPL and CNES on Titan balloons, and work at JPL on Venus balloons. But there is no work on Mars balloons (to my knowledge).

- In summary, I think we'll see a new planetary balloon mission some day given the high demand, but it will take time in the current budgetary climate to make it happen.

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