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Atmospheric test environments for planetary in-situ missions: Never quite "Test as you fly"

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Abstract

The planetary atmospheric and surface environments that planetary probes, landers and rovers may encounter cannot be perfectly replicated in tests on Earth. The temperature, pressure and composition of atmospheric test environments for previous missions are reviewed, and the differences between the conditions used in tests and the actual conditions at the target body are discussed. Generally, it has been the practice to replicate only those few key parameters that determine the phenomena of interest, and the effects of gravity and of minor atmospheric constituents are rarely simulated explicitly. Typically tests have been performed in nitrogen atmospheres (rather than carbon dioxide for Mars and Venus) or Helium (instead of hydrogen for Jupiter): exceptions are a handful of specific tests where the composition was considered critical. In-flight thermal anomalies are generally attributable to differences between the static conditions in a test chamber and the dynamic environment of flight, rather than to the composition of test atmospheres.

Keywords: Planetary probes; Landers; Atmospheres; Qualification testing; Thermal convection; Materials

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1. Introduction

More so than the vacuum of space familiar to satellite designers and operators, the atmospheric environments experienced in planetary exploration are often difficult to completely replicate. However, as many successful missions attest, careful design of the test conditions can affordably achieve the desired test objective, to simulate the relevant phenomena with sufficient fidelity to predict performance at another world. While being a laudable guideline, strict "Test as you fly" is, as Shakespeare put it in Hamlet, 'A custom more honoured in the breach than in the observance'. This paper reviews the atmospheric testing philosophy of previous missions with a view to indicating what has been accepted in the past as 'close enough'. The relatively few instances where in-flight performance has deviated from what was anticipated from test are also considered.

The paper considers only the descent and surface conditions for planetary probes and landers, particularly with respect to materials compatibility and thermal balance tests: the extreme aerothermal conditions of hypersonic planetary entry and testing of thermal protection materials have been more widely discussed previously.

2. Testing philosophy

To completely reproduce conditions on another planet requires first that those conditions be known, which is not always the case. Further, while individual aspects of an environment (e.g. pressure/temperature, or gravity) can be simulated in practicable test arrangements, it would be absurdly expensive, if not physically impossible, to achieve them all simultaneously. All one can reasonably do, and indeed all that has ever been done in 50 years of planetary exploration, is to attempt to match the performance of concern. This practice is well-established

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in aerodynamics, where scale model tests are used with confidence as long as the key parameters (e.g. Mach and Reynolds numbers) are achieved. Indeed, this dynamical similarity criterion has meant that some low-speed regimes for Venus probes can actually be usefully characterized by tests in liquid water rather than a wind tunnel. Table 1 summarizes some general test similarity criteria.

For planetary surface environments, generally the concerns have been regarding heat transfer, which is less deterministic when convective processes can occur in an atmosphere, than for the purely radiative-conductive transfers in vacuum. Some additional considerations include interactions with surface material (e.g. wheel systems, drills and samplers), plume impingement or sand-blasting, and electrical breakdown.

3. Environment testing on previous missions

The extent of testing programs associated with previous missions has depended on a number of factors. Perhaps most important is the unfamiliarity of the environment – the greater the difference in pressure and temperature from conditions either on Earth or in free space, the wider the range of environments that systems have to be designed to tolerate. Familiarity also embraces the cumulative experience of previous missions – the first US missions to Mars (Viking) and indeed the first European one (Beagle 2) received fairly intensive testing, whereas the benefit of some of that experience could be brought to bear on subsequent missions, with some issues no longer being considered of concern.

Another aspect is the scope of the program. Tightly cost-capped missions such as those in NASA's Discovery program may be able to afford less testing than 'Flagship' missions. Table 2 summarizes the test environments in a range of prior missions.

3.1. Venera

The Venus near-surface is perhaps the harshest atmospheric condition considered for planetary missions. The earliest Venera probes were designed for Venus atmospheres with lower pressures than turned out to be the case – for example the Venera 4 capsule was tested to 22 bar (e.g. Vakhnin, 1968: note that other accounts suggest a range of values for the early Veneras, e.g. Huntress and Marov, 2011 indicate that the Venera 4 design pressure was only 10 bar, but with expected margin to 18 bar). The thicker atmosphere may have crushed the probe (at 18 ± 2.5 bar) or the longer descent may have depleted the battery energy. From Venera 7 onwards, however, probes survived landing. Unfortunately, relatively little information is available on the specifications and testing environments used in the Soviet Venus program.

A few details on thermal testing are given by Zelenov et al. (2005); a general impression can also be gained from documentary footage available on video-sharing websites (e.g. Fig. 1). It appears that Veneras 4–8 (~1 m diameter) were tested at full scale in a thermal/pressure chamber, that operated to 500 °C (773 K) and 105 bar, but only subassemblies of the Veneras 9–14 and VEGA landers were tested (i.e. no lander-scale chamber was constructed or used on these larger [~2 m] vehicles.)

The Veneras used a combination of external and internal insulation. Because the performance of the external insulation depends on the gas that permeates it, tests had to be performed with CO_2 atmospheres (Zelenov et al., 1988; 2005), and the effect of the dynamic pressure of descent causing convective flow through the porous insulation had to be considered. A schematic of the test chamber is also indicated in Marov and Grinspoon (1998, p.62).

3.2. Viking

The first planetary (as opposed to lunar) lander program developed by NASA was Viking, which featured two softlanders at Mars in 1976.

It was noted in Morey and Tracey (1974) that wind generally cools the lander, but could cause heating during part of the day. However, it was considered sufficiently unlikely that wind would start and stop in a pathological pattern, so

Table 1
Test philosophy and similarity parameters.

Development aspect	Similarity desired (secondary criteria in parentheses)	Implementation & limitations
Solid-body aerodynamics	Mach & Reynolds Number (sometimes Knudsen number for hypersonics; sometimes Strouhal number for vortex-shedding Seiff et al. (1982)	Scale model wind tunnel tests; ballistic range tests; occasional full-scale drop test
Parachute characteristics (esp. inflation)	Dynamic Pressure and Mach Number (Reynolds Number; area loading/stiffness)	Wind tunnel test; drop test (usually full-scale)
Aerothermodynamics	Heat Flux, Shear (Mach, Reynolds Number)	Arcjet testing (usually coupon testing to assess material response, rather than to predict loads at different locations on a vehicle)
Thermal balance	Convective Heat Transfer Coefficient	Chamber tests at full scale. Gas density usually altered to compensate for effect of different gravity on free convection. Wind rarely simulated
Landing dynamics and ground interaction	Froude Number (Splashdown)	Drop test (scale model or full scale). Sandbox tests at full scale