THERMAL DESIGN AND PERFORMANCE OF PROBES IN THICK ATMOSPHERES : EXPERIENCE OF PIONEER VENUS, VENERA, GALILEO AND HUYGENS

Ralph D Lorenz [(1)], Bernie Bienstock [(2)], Patrice Couzin, Gerard Cluzet [(3)]

[(1)] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA, Email:rlorenz@lpl.arizona.edu
[(2)] The Boeing Company, El Segundo, California,USA. Email:bernard.bienstock@boeing.com
[(3)] Alcatel, Cannes, France A. Email:first.lastname@space.alcatel.fr

ABSTRACT

Probes that operate within dense planetary atmospheres, such as those of Jupiter, Titan and Venus, pose particular and unusual problems to the spacecraft thermal designer. In particular, radiation plays a much less dominant role in heat transfer, with free and forced convection tending to be more important. Convection is a much more empirical process than radiation, and thus ground testing assumes particular importance. We review the design of the Pioneer Venus probes, the Galileo probe and Huygens. We summarize the in-flight thermal performance of three missions as documented by housekeeping sensors. Some results from Venera missions are also reported.

1. INTRODUCTION

After the aerothermodynamic challenges of hypervelocity entry, descent thermal design can be the second most challenging aspect of a planetary probe [1]. Were a probe's internal equipment to attain thermal equilibrium with the environment, it would cease to function, and thus descent probes in these dense (or rather, optically-thick) environments must operate on a thermal transient. To a first order, the problem can be stated as an electrical analogy – the time constant over which the probe can operate before overheating or overcooling is given by the product RC, where R is the resistance to heat flow (pathway length, divided by conductivity times area) and C is the heat capacity. The challenge is then to maximize R and C within the design constraints of the mission.

The Pioneer Venus probes were sealed pressure vessels, and used internal multilayer thermal insulation blankets together with heat sinks (including the use of beryllium structure and Xenon fill gas) to keep temperature rise in the dense, hot Venus atmosphere to a tolerable levels. The thermal performance of these spacecraft was excellent.

The Galileo Probe adopted a different approach, with sealed experiment units inside an unsealed descent module. The temperature rise rate, and the associated thermal gradients across the probe, challenged the accuracy of the scientific instruments, requiring a lengthy recalibration campaign post-mission. Nonetheless, the probe continued to operate to beyond the nominal specified depth.

The Huygens probe was also unsealed, and incorporated foam insulation to minimize heat loss to the cold Titan environment. Fractionally warmer than predicted, the probe's internal thermal environment was very benign and permitted a long post-impact surface mission. Heat transfer from the probe decreased markedly at the end of descent, due to the cessation of forced convection due to the probe's descent velocity.

In some cases (such as Galileo), it appears internal convective heat transfer is substantially higher during their descent than in laboratory conditions on Earth. Even though one might expect there to be little or no effect, it seems that turbulent fluctuations in pressure and other effects enhance the flow of gas, and thus heat, between inside and outside, and between elements inside. In the case of Huygens, for which data is still being evaluated, it may be that heat transfer through experiments exposed to the environment may be a major factor..

2. PIONEER VENUS

The Pioneer Venus mission featured one large probe (with a parachute to prolong its descent at high altitudes and extract the probe from its entry heat shield) and three small probes which retained their shields. These were separated sequentially on Venus approach from a spinning carrier spacecraft to yield different aim points on Venus (the small probes being "Day","Night" and "North").

The overall design of the Pioneer Venus probes is described in [1] and [2]. The thermal design of the large probe is discussed in some detail in [3].

In brief, the interior of the large probe pressure vessel was lined with 41 layers of aluminized Kapton MLI to act as a barrier to radiation and convection. Structural penetrations of the blanket were made with Titanium to minimize conductive shorts. These features increased 'R'. The 'C' term in the equation was maximized by using beryllium for the equipment shelves. This metal, although difficult to work with, has a heat capacity of some 2000 J/kgK – double that of Aluminium.

The MLI performance was tested with a nitrogen atmosphere, and with nitrogen+helium (since one of the experiments vented helium into the probe during descent.) This allowed the analytical thermal model to be updated, since the conductivity of helium is much higher than nitrogen by a known factor. Other tests showed free convection heat transfer coefficients for internal surfaces of 0.5 to 2 BT/hr-ft2-F

The destructive effects of physical simulation to the full 900F made it necessary to limit tests to 500F : when that temperature was reached the test was prolonged to permit internal temperatures to rise to the levels expected during the real descent. A thermal test model (TTM) was used for initial design verification. Note that because of the thermal sealing, electrical tests of the probe were limited to less than 2 hours [2] except when special cold nitrogen cooling was used.

During a descent test on the flight unit, some of the internal heat transfer was found to be lower than the TTM or analysis suggested. One factor was believed to be the role of the cable harness in impeding gas flow [3].

Flight temperature data and the predictions are shown in figure 1. Data – previously unpublished – are taken from [4]. Plots are referred to time of first loss of signal – data were sent prior to the short entry phase, during which time the plasma sheath caused a radio blackout. This forms the time reference.

The three small probes clearly had a higher area:volume ratio. Accordingly, they needed thicker thermal blankets (61 layers). On both large and small probes the MLI blankets were held in place against the high entry g-loads by Titanium retainers. A second measure to decrease the internal heat transfer was the substitution of Xenon for nitrogen as the fill gas.

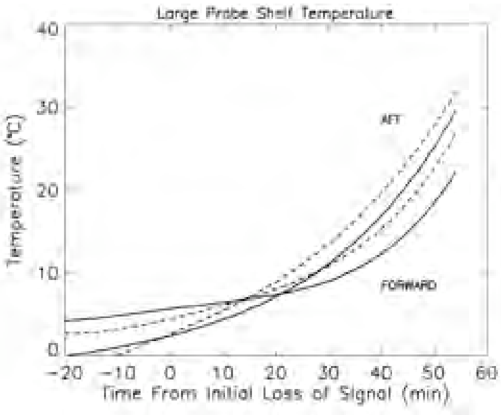

Figure 1. PV large probe temperature history for the forward and aft shelves. Solid line are actuals – dashed are predictions. The probe started off slightly warmer than predicted (see Huygens later) but the temperature rise was slightly lower than expected.

Xenon, with a high relative molecular mass, has a low thermal conductivity. (Its breakdown potential is quite low, which would be problematic for the high voltages associated with the large probe's neutral mass spectrometer : the large probe retained nitrogen as the fill gas.)

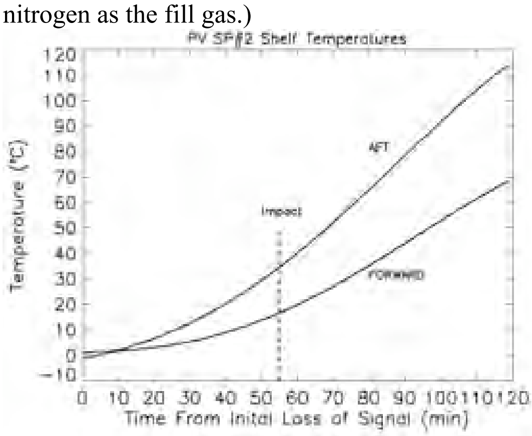

Figure 2. Small probe 2 (day probe) temperature history – the probe failed an hour after impact, with temperatures at 115 and 70C.

The pressure inside all of the probes increased during their missions. The temperature rise of the gas, were it at the shelf temperature, would account for an ideal-gas pressure rise of only ~10-25%. The increase of ~50% implies the gas itself was considerably hotter than the shelf (as expected) although possible outgassing from materials (e.g. mylar may lose ~2% by mass as water) or small leaks may have also been a factor.

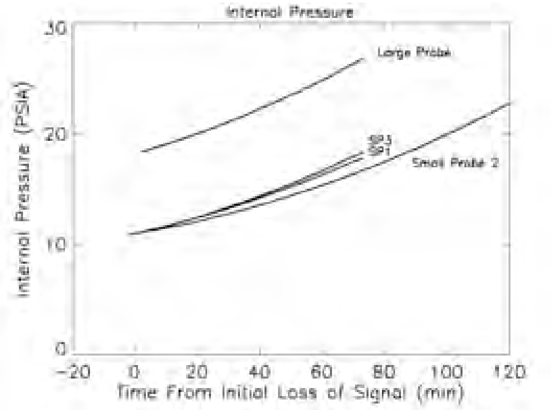

Figure 3. Internal pressure histories of the probes.

It is notable that small probe 2 (the Day probe) survived for some 70 minutes after landing. As the probe internal temperature increased, the battery voltage rose to 30.8 Volts. However, the current consumed dropped, together with the signal strength of the signal received on Earth, suggesting that a power amplifier component failed [2].

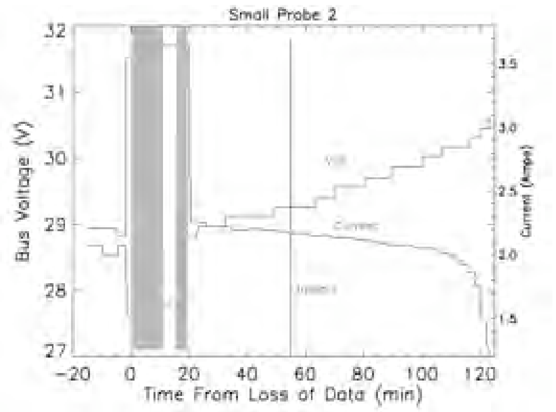

Figure 4. Voltage/Current history of the day probe, suggesting transmitter failure as 'cause of death'.

3. VENERA

The Russian Venus probes faced the same design challenges (indeed, more severe ones, since operation after impact was desired).

The Veneras [5] incorporated insulation both internal and external to the pressure vessel, and phase change materials (lithium nitrate trihydrate) to further buffer the temperatures, especially adjacent to units with high power dissipation.

A fan maintained circulation of the air inside the pressure vessel to ensure even distribution of temperature and the efficient function of the phase-change heat sink.

The insulation used on the exterior was a bonded porous silica material (which would remain rigid, and insulating, in the face of mechanical loads during entry and descent). A special coating (presumably something like a sealant) was applied to minimize the effect of ventilating the insulation during the descent.

The density of the Venus atmosphere, together with the earth-like gravity, leads to fairly high Reynolds numbers during descent. Heat transfer coefficients were therefore very high, of the order 150-1000 $Wm^{-2}K^{-1}$ and the temperature of the probe surface was therefore almost exactly the same as the ambient air.

As can be seen from fig.5 , the internal temperature fell well within the region expected from ground testing.

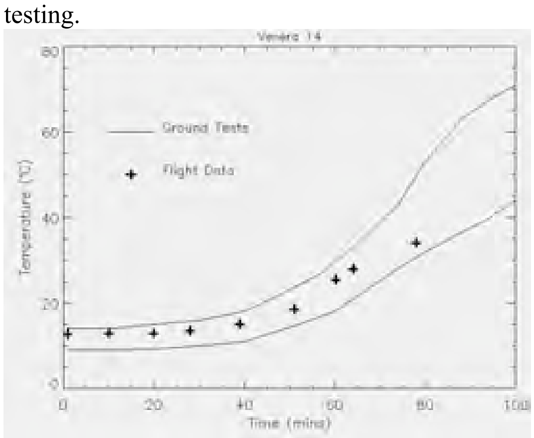

Figure 5. Venera 14 internal temperature history.

The designers note [5[that towards the end of the probe's operational life on the surface, the temperatures in the upper hemisphere of the pressure vessel exceeded those in the lower hemisphere by some 70-100 ^{o}C. Also, in the 'scientific apparatus container' (which did not have forced ventilation by a fan) some hotspots developed : some hotspots also formed in the instrument container where structural components required the insulation to be thinner than elsewhere – these spots were 20-35^{o}C warmer than their surrounds.

4. GALILEO

The Galileo probe, although owing considerable heritage to the Pioneer Venus experience, adopted a different thermal design approach : rather than build a probe that is a pressure vessel, the probe itself was open, and individual equipment boxes were sealed. A brief review of the probe design is given in [1].

Scaling of pressure forces suggests this approach has some design merit – smaller boxes of a given wall thickness can withstand higher pressures. It also conveniently transfers the problem of sampling aperture and window design (a major challenge in Pioneer Venus, which needed sapphire and diamond windows) from the probe contractor to the individual experimenters. Note also that the Galileo probe did not have to endure pressures nearly as high as Pioneer Venus.

Some of the thermal testing associated with Galileo, as well as a somewhat obscure heating effect (namely heating by adiabatic compression, as air progressively leaks into the probe volume and raises its pressure) are described in [6]. Additional discussion of testing and flight performance is presented in [7].

Some Galileo Probe housekeeping temperatures are available on the Planetary Data System (PDS) via the Atmospheric Structure Instrument [8,9]. The relevant data product is ASI.PDS.F.HK.02 and are plotted in figure 6 at the end of this paper.

The temperature labelled 'Taero' is from a temperature sensor mounted on the inside of the Descent Module outer skin. This was to provide some sort of back-up to the ASI atmospheric temperature sensors : it followed the ASI sensors with a lag of ~ 1minute or <10K.

The curves labelled 'Shelf T1' and 'Shelf T2' are from temperature sensor mounted on the coupling nut connecting the inlet pressure manifold to the high range (P3) pressure sensor and from a temperature sensor mounted on the instrument mounting shelf adjacent to the science atmospheric temperature sensor mounting position respectively.

The temperature rise in the probe was higher than indicated in ground tests, and the temperature rates and gradients were such that some instruments had to be recalibrated on the ground. (Some, such as the Helium Abundance Detector, did not as it had a particularly robust thermal design – a beryllium structure with a foam insulation thermal blanket.)

This enhanced heat transfer has several contributing factors [7]. One is that the pre-chill procedure that could be implemented on the ground was warmer but longer than in flight. Jupiter's higher gravity may have enhanced internal convection, but the dominant factor was probably probe buffeting during descent (leading to mechanical agitation) and pressure fluctuations driving flow through the various penetrations of the probe hull. These aspects are of course challenging to test on the ground, and their importance (except gravity) not immediately obvious.

The probe battery temperatures rose from 0 to about 49^{o}C (Battery 3 only 30^{o}C). The processor temperature range were about 10^{o}C further in each direction. Transmitter B was lost at 49 minutes : even though transmitter A had been tested to only 60^{o}C, it continued to operate to 59 minutes, when it failed at 115^{o}C [7] – the same temperature as PV2!

5. HUYGENS

The Huygens probe [10,11,12] differs fundamentally from the previous two examples in several respects : first, the atmosphere has a relatively benign composition (N2, CH4, no corrosive gases) and pressure, such that sealing is not necessary, and second, that the Titan environment is fundamentally a cold one, in contrast to the hot, deep atmospheres of Venus and Jupiter. An additional related aspect which affects the structural design is the large scale height of the atmosphere, leading to modest (~15g) entry loads.

The Huygens probe structure is essentially two honeycomb equipment shelves (these have only a stiffness function, not as thermal ballast). The top platform, exposed to the outside after the heat shield has been jettisoned, carries the parachutes, mortar, and antennae. The larger experiment platform forms the core structure to which most equipment (CDMS, power, experiments etc.) are attached. This is linked to the top platform by a set of three rods. A thin (~1mm) aluminium fore dome defines the aerodynamic shape, and is attached to the experiment platform via three load-bearing but thermally isolating fibreglass standoffs. The fore dome is linked to the top platform, and the aerodynamic shape completed, by a stiffened aluminium alloy frustum.

Apertures such as experiment inlets (linked mechanically to the experiment platform) are sealed to the foredome by flexible metal bellows. A 6 cm2 vent hole on the top platform serves to equalize pressure during launch and descent.

The flight performance was excellent (figure 7) – internal temperatures remained benign throughout the mission. Temperatures at the start of descent were fractionally warmer (~7C) than predicted, a factor which probably improved the battery performance substantially. This warmth may have been due to unmodelled solar reflections on the back of the heat shield which was illuminated during the coast.

Cooling by forced convection increased progressively during descent as the air becomes denser. After landing, the heat loss from the probe slows appreciably, allowing a constraint to be derived on near-surface windspeeds [12].

There is some evidence that the heat leak through some experiments was higher than budgeted. Forced convection effects not reproduced in ground tests may be responsible, although the net impact was not significant.

6. DISCUSSION - COMMON THEMES

An exotic arsenal of techniques have been applied in thermal management of probes, including use of beryllium, phase change materials and a variety of insulation types. Although in retrospect some thermal designs could have been improved (e.g. Galileo) they have generally met all requirements.

One striking, but not widely-reported, finding herein is that convective heat transfer inside vented probes is often substantially higher during their descent than in laboratory conditions on Earth. Even though one might expect there to be little or no effect, it seems that turbulent fluctuations in pressure and other effects enhance the flow of gas, and thus heat, between inside and outside, and between elements inside.

This and the other difficulties of thermal design underscore the difficulty and importance of thermal testing. Probes are engineering experiments as well as scientific platforms.

7. ACKNOWLEDGEMENTS

RDL acknowledges the support of the Cassini project, and the assistance of Helen Fan in digitizing and plotting archive data. We appreciate the comments of Lee Hennis.

8. REFERENCES

1. Bienstock, B., Pioneer Venus and Galileo Entry Probe Heritage, Proceedings of the International Workshop "Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science" Lisbon, Portugal 6-9 October 2003, ESA SP-544, February 2004 pp.37-45

2. R. F. Brodsky (ed), Pioneer Venus Case Study in Spacecraft Design, AIAA Professional Study Series, 1979

3. L. A. Hennis and M. N. Varon, , Thermal Design and Development of the Pioneer Venus Large Probe, in Thermophysics and Thermal Control (R. Visjanta, ed) Vol.65 of Progress in Astronautics and Aeronautics, AIAA (Presented as Paper 78-916 at the 2nd AIAA/ASME Thermophysics and Heat Transfer Conference, Palo Alto, California, May 24-26, 1978)

4. C. M. Meredith, A Not-So-Quick Look at the Probes Descent Data, Hughes Aircraft Corporation Interdepartmental Correspondence HS507-7982, 16 January 1979.

5. I. A. Zelenov, A. F. Klishin, V. M. Kovtunenko and A. F. Shabarchin, Methods of Providing for Thermal Conditions in teh Venera Automatic Interplanetary Stations when in the Atmosphere of Venus, Kosmicheskie Issledovania, 26, 33-36, Jan-Feb 1988.

[6] R P Bobco, Free Convection in Enclosures Exposed to Compressive Heating, AIAA-80-1536, AIAA 15th Thermophysics Conference, July 14-16, Snowmass, CO, 1980

7. Hughes Aircraft Corporation, Galileo Mission Operations Final Report, 1996

8. Seiff, A.and Knight, T.C.D.: 1992, The Galileo probe atmosphere structure instrument, Space Science Reviews, 60, 203.

9. Seiff, A., et al. 1998, Thermal Structure of Jupiter's atmosphere near the edge of a 5 micro-metre hot spot in the north equatorial bellt, J. Geophys. Res., 103, 22,857.

10. J. Doenecke, M. Elsner, Special Heat Transfer Problems within the Huygens Probe, Proceedings, 4th European Symposium on Space Environmental Control Systems, pp. 279-283

11. Jones J C and F Giovagnoli, Huygens Probe System Design, in Wilson, A. (ed0, Huygens, Science, Payload and Mission, ESA SP-1177, Noordwijk, The Netherlands, 1997.

12. R D Lorenz, Thermal Interactions of the Huygens Probe with the Titan Environment, Icarus\, submitted 2005.

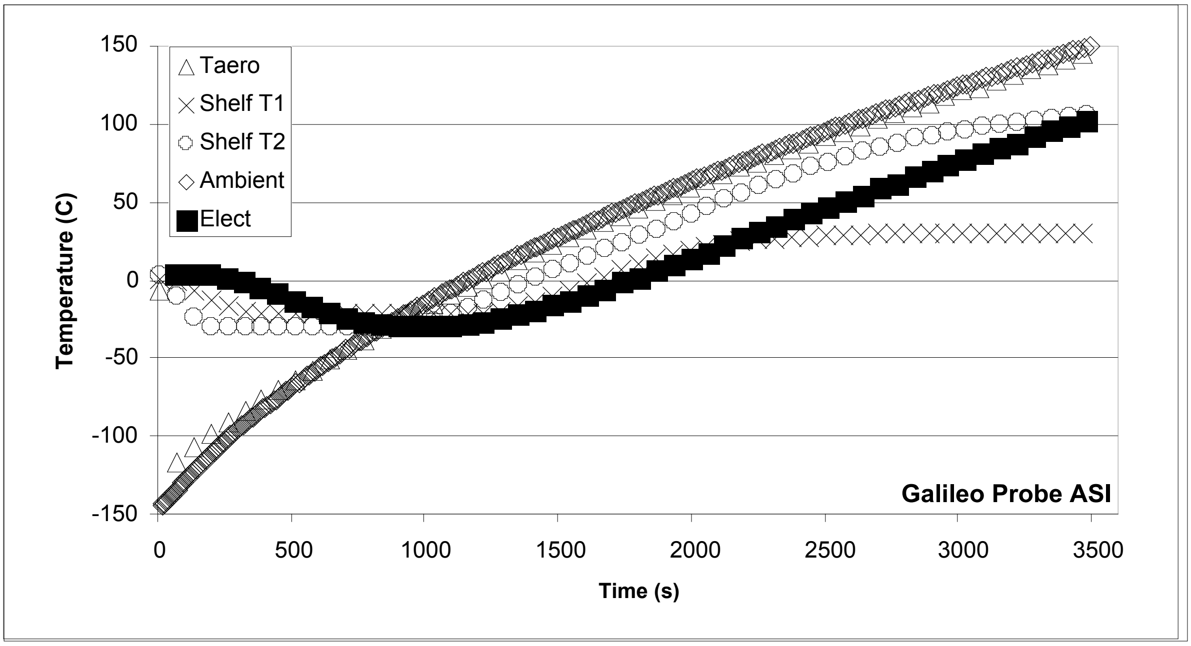

Figure 6. Galileo Temperatures from the ASI instrument – most of the probe system equipment such as computer and batteries most closely follows the benign shelf temperature T1.

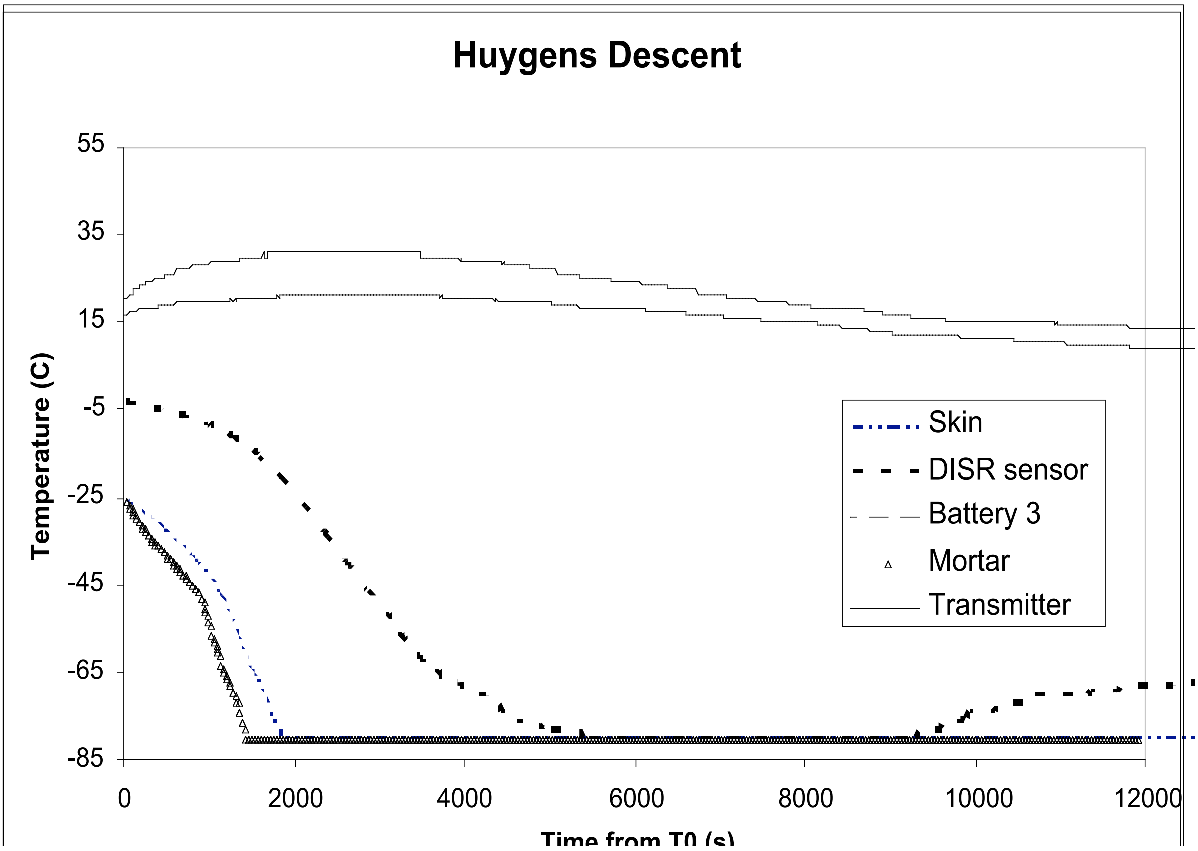

Figure 8. Huygens Probe temperatures (external sensors saturated at -80C) Notice the DISR sensor head temperature rises after impact (at 8870s) due to the drastic reduction in convective cooling on the ground. Internal temperatures (battery, transmitter) show a small change in slope at this time but are always benign.