Abstract

The ESA Huygens Probe is due for launch as part of the NASA/ESA Cassini mission in 1997, to arrive at Titan in late 2004, and will make a 2–2.5 h exploratory descent to the surface. However, the state of Titan's surface is largely unknown and it may be at least partially covered in liquid hydrocarbons. With such ignorance of the surface state, and the limited financial envelope of the project, it is not practicable to design the Probe to 'soft-land'. Survival may, nevertheless, be possible and this paper presents various impact-dynamics analysis methods and assesses the likely impact scenarios and their survivability.

It is concluded that the Probe has a good chance of surviving to continue its scientific mission from the surface. The scientific information about the surface that could be gathered from impact-dynamics measurements is also discussed.
1. Introduction

The Huygens Probe\(^1\) will make a 2.25 h (nominal) descent to the surface of Saturn's enigmatic moon Titan (Fig. 1), which it will hit with a vertical velocity of about 5 m/s. Although for cost and complexity reasons post-impact survival has never been a design driver for the Probe, it has long been realised that survival is possible\(^3\), and at the current stage in Probe development (early Phase-C/D; i.e. main development phase) prospects for a productive surface mission look relatively good, with a modest impact velocity and healthy energy and link margins. In the event of Probe survival, a surface mission lasting of the order of 30 min should be possible.

Thus a major factor in the surface mission becomes the load sustained by the Probe at impact. Both the energy and momentum of the descent must be dissipated, where they are dissipated depends largely on the relative hardiness or strengths of the Probe and the surface. Ideally, dissipation would occur in the material on which the Probe must land, which will happen in the event of a soft surface material.

An earlier paper\(^9\) has reviewed the likely surface types to be encountered on Titan. Here I examine the range of expected impact parameters and loads, and the likely effects on the Probe and its payload. The most up-to-date and comprehensive descriptions of the Probe and its payload are to be found in two recent articles in ESA Bulletin No. 77, February 1994\(^9,10\).

The aims of the present paper are to:

- summarise work on spacecraft impact dynamics, on which the literature is sparse and scattered
- investigate the impact dynamics of the Huygens Probe, in order to assess the likelihood of its survival on the surface of Titan
- examine the variation in impact deceleration with surface mechanical properties to see how acceleration measurements on the Probe can be used to measure these properties.
Some useful comparisons may be drawn with previous planetary missions to put the Huygens landing scenario in context. A convenient summary of planetary missions is that by Wilson.\(^1\)

Luna 9, the first man-made object to have survived on the lunar surface, hit at approx. 6 ms\(^{-1}\). Its internal equipment was ‘protected by shock-absorbers’. It had a mass of about 100 kg. Luna 16 (an automatic sample return) and its successors were considerably larger, and soft-landed at about 2.5 ms\(^{-1}\).

The Surveyor spacecraft had shock-absorbing legs and a propulsion system for soft-landing on the Moon; at touchdown they weighed just under 300 kg, and had vertical velocities of the order of 3 ms\(^{-1}\). The main-structure loads were 8–20 g, although load-amplification effects on the spidery lander led to loads on the antenna and solar array (mounted on a mast) of the order of 90 g. The Viking landers on Mars (equipped with a throttleable hydrazine retro-rocket system, and shock-absorbing legs for soft-landing) touched down at about 2.5 ms\(^{-1}\).

The Pioneer Venus (PV) probes have many similarities with the Huygens Probe, and a detailed comparison is given in a following section. They, and the Russian Venera probes, hit the surface of Venus at about 9 ms\(^{-1}\), relying only on aerodynamic drag to brake their descent, and weighed between 93 kg (PV small probes) and 700 kg (Venera). The pictures sent back by the Veneras suggest they landed on rock slabs (possibly covered with some dust); these probes recorded landing loads\(^3\) of up to 75 g.

Of the 30 or so missions described above, only Luna 18, Mars 2, and three of the four Pioneer Venus probes failed completely at impact (Table 1). Veneras 11 and 12 appear to have suffered extensive instrument failures on landing; Mars 3 sent back 20 s of (blank) TV signals before failing, and the sampler of Luna 25 was damaged by a rough landing. It is noteworthy that if spacecraft survived for a few seconds on the surface, they generally continued to function up to and often beyond their design life, with some missions being terminated either by command from Earth, or by relay spacecraft passing out of sight.

The impact velocity of the Huygens Probe is only slightly higher than that of ‘true’ soft-landers, and rather less than for several previous ‘hard’ or ‘semi-hard’ landers on the Moon and Venus. Thus, in relative terms, prospects for Huygens survival seem quite good, even though it has not been designed with impact survival in mind.

The NASA Pioneer Venus multi-probe mission is perhaps the most useful analogue for the Huygens impact: in part because the masses and velocities are comparable (Pioneer Venus, though robust, was not designed to survive impact), and because (unlike the Russian Mars and Venus missions) it is relatively well-documented in the open literature\(^\text{13} \text{-} 15\).

Four Pioneer Venus probes (three small and one large) were sent to Venus. The large probe was spherical (73 cm diameter) and had a mass of 310 kg (including its 1.4 m diameter heat shield, which it released after deploying a parachute). The small probes (50 cm diameter; 90 kg) descended without parachutes and kept their 76 cm-diameter, 45° half-angle entry protection shields attached throughout their descent.

The probes all transmitted directly to Earth using antennas with approximately hemispherical coverage\(^5\). The dispersion of the probes over the surface of Venus was such that the Earth (where the signals were received) was about 30° above the horizon over each landing site (except, significantly, for the day probe, where the Earth elevation was about 40°).

The probes impacted the surface at velocities of approximately 9–10 m/s, impact being indicated by a sudden change in the Doppler shift of the received radio frequency. Signals from two of them (the large probe and the north probe) were lost at impact. Signals were received from the north probe for 2 s after impact, but the day probe continued to transmit for 67 min, at which time its internal temperature reached 126°C. Telemetry suggests that the signal was lost at this point not due to battery exhaustion, but due to thermal failure of a power-amplifier component\(^1\).

2. Comparisons with previous missions

3. Comparisons with Pioneer Venus
Table 1. Previous missions to planetary surfaces

<table>
<thead>
<tr>
<th>Year</th>
<th>Mission</th>
<th>Nation</th>
<th>Target</th>
<th>Mass (kg)</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966</td>
<td>Luna 9</td>
<td>USSR</td>
<td>Moon</td>
<td>~ 100</td>
<td>Sphere 58 cm diam.</td>
</tr>
<tr>
<td>1966</td>
<td>Surveyor 1</td>
<td>US</td>
<td>Moon</td>
<td>203</td>
<td>Tripod, 3 m high, 4 m across</td>
</tr>
<tr>
<td>1966</td>
<td>Surveyor 2</td>
<td>USSR</td>
<td>Moon</td>
<td>116</td>
<td>Footpads 30 cm diam.</td>
</tr>
<tr>
<td>1967</td>
<td>Surveyor 3</td>
<td>US</td>
<td>Moon</td>
<td>293</td>
<td>As Surveyor 1</td>
</tr>
<tr>
<td>1967</td>
<td>Surveyor 4</td>
<td>US</td>
<td>Moon</td>
<td>293</td>
<td>As Surveyor 1</td>
</tr>
<tr>
<td>1967</td>
<td>Surveyor 5</td>
<td>US</td>
<td>Moon</td>
<td>305</td>
<td>As Surveyor 1</td>
</tr>
<tr>
<td>1967</td>
<td>Surveyor 6</td>
<td>US</td>
<td>Moon</td>
<td>300</td>
<td>As Surveyor 1</td>
</tr>
<tr>
<td>1968</td>
<td>Surveyor 7</td>
<td>US</td>
<td>Moon</td>
<td>305</td>
<td>As Surveyor 1</td>
</tr>
<tr>
<td>1969</td>
<td>Luna 15</td>
<td>USSR</td>
<td>Moon</td>
<td>As Luna 16?</td>
<td></td>
</tr>
<tr>
<td>1970</td>
<td>Venera 7</td>
<td>USSR</td>
<td>Venus</td>
<td>~ 500</td>
<td>Sphere 1 m diam.?</td>
</tr>
<tr>
<td>1970</td>
<td>Luna 16</td>
<td>USSR</td>
<td>Moon</td>
<td>1880</td>
<td>4 m-square platform</td>
</tr>
<tr>
<td>1970</td>
<td>Luna 17</td>
<td>USSR</td>
<td>Moon</td>
<td>As Luna 16?</td>
<td></td>
</tr>
<tr>
<td>1971</td>
<td>Mars 2</td>
<td>USSR</td>
<td>Mars</td>
<td>450</td>
<td>1.2 m diam.</td>
</tr>
<tr>
<td>1971</td>
<td>Mars 3</td>
<td>USSR</td>
<td>Mars</td>
<td>450</td>
<td>1.2 m diam.</td>
</tr>
<tr>
<td>1971</td>
<td>Luna 18</td>
<td>USSR</td>
<td>Moon</td>
<td>As Luna 16</td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>Luna 20</td>
<td>USSR</td>
<td>Moon</td>
<td>As Luna 16</td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>Venera 8</td>
<td>USSR</td>
<td>Venus</td>
<td>495</td>
<td>As Venera 7</td>
</tr>
<tr>
<td>1973</td>
<td>Luna 21</td>
<td>USSR</td>
<td>Moon</td>
<td>As Luna 17</td>
<td></td>
</tr>
<tr>
<td>1973</td>
<td>Mars 6</td>
<td>USSR</td>
<td>Mars</td>
<td>450</td>
<td>As Venera 7</td>
</tr>
<tr>
<td>1974</td>
<td>Luna 23</td>
<td>USSR</td>
<td>Moon</td>
<td>As Luna 16</td>
<td></td>
</tr>
<tr>
<td>1975</td>
<td>Venera 9</td>
<td>USSR</td>
<td>Venus</td>
<td>660</td>
<td>2.1 m disc + 1 m sphere</td>
</tr>
<tr>
<td>1975</td>
<td>Venera 10</td>
<td>USSR</td>
<td>Venus</td>
<td>660</td>
<td>As Venera 9</td>
</tr>
<tr>
<td>1975</td>
<td>Viking 1</td>
<td>US</td>
<td>Mars</td>
<td>612</td>
<td>2.1 m tall, 3 m wide</td>
</tr>
<tr>
<td>1975</td>
<td>Viking 2</td>
<td>US</td>
<td>Mars</td>
<td>612</td>
<td>3 footpads, 31 cm diam.</td>
</tr>
<tr>
<td>1976</td>
<td>Luna 24</td>
<td>USSR</td>
<td>Moon</td>
<td>As Luna 16</td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>PV Large</td>
<td>US</td>
<td>Venus</td>
<td>316</td>
<td>Sphere 73 cm diam.</td>
</tr>
<tr>
<td>1978</td>
<td>PV Day</td>
<td>US</td>
<td>Venus</td>
<td>93</td>
<td>50 cm diam, with 76 cm diam. coaxial nose</td>
</tr>
<tr>
<td>1978</td>
<td>PV Night</td>
<td>US</td>
<td>Venus</td>
<td>93</td>
<td>As PV Day Probe</td>
</tr>
<tr>
<td>1978</td>
<td>PV North</td>
<td>US</td>
<td>Venus</td>
<td>93</td>
<td>As PV Day Probe</td>
</tr>
<tr>
<td>1978</td>
<td>Venera 11</td>
<td>USSR</td>
<td>Venus</td>
<td>7002?</td>
<td>As Venera 9?</td>
</tr>
<tr>
<td>1978</td>
<td>Venera 12</td>
<td>USSR</td>
<td>Venus</td>
<td>7002?</td>
<td>As Venera 9?</td>
</tr>
<tr>
<td>1981</td>
<td>Venera 13</td>
<td>USSR</td>
<td>Venus</td>
<td>760</td>
<td>As Venera 9?</td>
</tr>
<tr>
<td>1981</td>
<td>Venera 14</td>
<td>USSR</td>
<td>Venus</td>
<td>760</td>
<td>As Venera 9?</td>
</tr>
<tr>
<td>1984</td>
<td>Vega 1</td>
<td>USSR</td>
<td>Venus</td>
<td>760</td>
<td>As Venera 9?</td>
</tr>
<tr>
<td>1984</td>
<td>Vega 2</td>
<td>USSR</td>
<td>Venus</td>
<td>760</td>
<td>As Venera 9?</td>
</tr>
</tbody>
</table>

On the one hand, the Pioneer Venus probes were more robustly built than Huygens; the small probes having to endure entry accelerations of the order of 560 g. Also, the probes were built as spherical pressure vessels (the shells were of titanium, several millimetres thick), able to withstand the 200 bar surface pressure at Venus. Huygens has much more modest entry loads (of order 20 g) and has a thin outer aluminium shell which is not sealed.

On the other hand, the Huygens impact velocity will be lower by a factor of almost 2. Secondly, pictures from the Soviet Venera spacecraft (which had broadly similar impact velocities but were equipped with impact-attenuation systems) indicate a very unpleasant surface on which to land, strewn with boulders and large slabs of volcanic rock (see Ref. 8, Fig. 12). Hopefully Titan’s surface may be more forgiving!

The two failures that occurred at impact are probably a result either of impact damage directly, or the tipping-over of the probes at impact such that the Earth was no longer in the main antenna lobe. The failure of the night probe 2 s after impact may have been due to tipping over, or perhaps to thermal failure following inundation of the hot (600 K) atmosphere if the pressure vessel was ruptured by the impact.

Thus a major contributing factor to the loss-of-signal of the Pioneer Venus probes
<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>Comments</th>
</tr>
</thead>
</table>
| < 3        | 8 h of contact over 3 d  
True soft-landing. Operated for 6 months |
| < 3        | Impact accelerometry recorded soil structure to depth of 20–30 cm |
| < 2        | Bounced 30 cm at landing (engines on); OK after engines turned off by ground command |
| known      | Contact lost 2.5 min before landing, although automatic landing may have been successful |
| 2–4        | Pressurant leak forced late retro sequence |
| 4–8        | Crashed |
| 8–10       | Telemetry multiplexer failure — only temperature data (23 min) from surface. Bad attitude caused 20 dB signal loss (rolled in wind?) |
| 10–15      | Sample-return mission |
| 15–20      | Rover mission |
| 20–30      | Crashed (dust storm?) |
| 30–40      | Transmissions discontinued after 20 s; high winds, or failure of relay orbiter? |
| 40–50      | Crashed ‘due to rugged terrain’ |
| 50–70      | Operated for 50 min |
| 70–90      | Contact lost before landing  
Rough landing damaged drill |
| 90–110     | First pictures from Venus, lasted 53 min |
| 110–140    | Operated for at least 65 min (relay passed out of sight) |
| 140–170    | Operated until 1982 |
| 170–200    | Shut down 1980 |
| 200–250    | Failed at impact |
| 250–300    | Operated for 67 min on surface; thermal failure? |
| 300–350    | Operated for 2 s |
| 350–400    | Failed at impact |
| 400–450    | Instrument failures on landing; operated 95 min |
| 450–500    | Instrument failures on landing; operated 110 min |
| 500–600    | Operated for 127 min |
| 600–700    | Operated for 57 min |
| 700–800    | Drill sequence started prematurely; no surface science |
| 800–900    | Operated for 57 min |

may well have been the presence of the entry shields on the small probes causing antenna depointing at impact. Indeed, Venus surface data was recovered from what was originally thought to be noise, when the Venera 7 lander’s telemetry signal fell to 1% of its nominal value at impact. Because Huygens is a relatively flat and soft-bottomed spacecraft, we might expect that (except in the case of extremely steep or rocky surfaces) such antenna depointing is unlikely. Further, since the cold Titan atmosphere is much less harsh than the dense, scorching atmosphere on Venus, thermal failure should be at least slower, and perhaps less likely, to occur on Huygens.

A substantial amount of work has been performed on impact dynamics for military applications. Most civil work is in connection with safety engineering, for aircraft and automotive crashes, and the accidental dropping of flasks used to transport radioactive waste. Comparatively little work is reported in the open literature in the West on the impact dynamics of spacecraft (Ref. 22 gives some general information; see references hereafter for particular cases).
The bulk of the available work was performed in connection with the US Mercury, Apollo and Surveyor programmes, although some recent ESA-sponsored studies have been performed on Mars penetrator/landers. For the Mercury and later Apollo programmes, the work was focussed on estimating impact loads to ensure crew survival, both for the nominal sea landing and for possible impact on land in the event of a launch abort.

As part of the Apollo Programme, models of the mechanical properties of the lunar surface had to be developed (there were initial fears that the surface might be so soft that a spacecraft, or astronauts not equipped with snowshoes, might sink into it) and the Surveyor series of soft-lander missions was designed to assess the lunar surface in preparation for the manned Apollo landings. Some instrumentation (strain gauges on the landing legs and accelerometers on the main body) was devoted to measuring landing loads to assess the bearing strength of the surface. Further indications of soil physical properties were obtained by photographing the 'feet' of the landing legs to measure foot penetration and ejecta throwout, and by measuring motor currents on the sampling arm.

Most of the Apollo and Mercury work was devoted to liquid landings (which were, of course, the nominal mode of ending their missions). Analytic simulation of such landings became well-developed and predictions for Huygens are made in a following section.

Simulation of landings on solid surfaces is rather more difficult and available data is more scarce. First, since the 'hardness' of the surface is comparable with that of the spacecraft, the partitioning of energy and momentum dissipation between the vehicle and the surface becomes complex, so analytical treatment is extremely difficult (although Ref. 26 provides an instructive analysis of a simple case). Secondly, the higher impact loads generally cause damage to the spacecraft, such that even for small-scale models, large series of tests are prohibitively expensive, so there is relatively little available experimental data. Modern finite-element techniques allow the detailed investigation of impact dynamics and structural response, but are also expensive.

In the following sections, relatively simple methods of estimating the loads and response of an impacting spacecraft are presented, with Huygens as the example. While relatively simple, these methods offer useful insight into what may occur at the climax of the Huygens mission.

5. Impact conditions

The Huygens Probe (Figs. 2–4), during most of its descent, is suspended beneath a stabilising drogue parachute (a polyester/kevlar disk-gate-bag chute with a reference diameter of 2.45 m)\(^2\). The terminal velocity of the Probe with parachute at the surface of Titan, with a surface gravity of 1.35 ms\(^{-2}\) and an atmospheric density of 5.3 kg m\(^{-3}\), is 5.2 ms\(^{-1}\) (approximately the velocity attained on Earth by an object dropped from a height of 130 cm, which is convenient for impact testing!). This is about half of the impact velocity of the Apollo capsules and the Pioneer Venus spacecraft.

There is some uncertainty in the radio-occultation data from the Voyager encounter, and a consequent uncertainty in the knowledge of the atmospheric density\(^2\), which could be 4.57–6.01 kg m\(^{-3}\). Similarly, there is a 10% uncertainty in the drag performance of the parachute, and so combining these uncertainties gives the terminal velocity of the Probe at the surface between 4.6 and 5.8 ms\(^{-1}\).

The horizontal velocity of the Probe is unlikely to be exactly zero as parachutes tend to have a slight 'gliding' action, but certainly the sideways component will be small (say 1 ms\(^{-1}\)). The Probe will be moving along with any winds at the surface, but these (e.g. Ref. 29) are likely to be very small (again 1 ms\(^{-1}\)). The specification on the stabiliser requires it to have pendulum-type oscillations of less than 10° amplitude. Should a wind gust cause a swing greater than this, it should return to within 10° of vertical within about 10 s. Wind gusts near the surface are unlikely anyhow, so for the purposes of this study it is assumed that the impact attitude is vertical, and the corresponding horizontal velocity component is zero.

The Probe mass at impact is expected to be about 207 kg, and its transverse moment of inertia is about 20 kgm\(^2\).
Figure 2. Exploded view of the Huygens Probe. The 2.7 m diameter front shield and an aft cover protect the Probe during entry. The Probe's descent module comprises a round fore-dome and a conical aft section: a top platform carries the two antennas and the parachute box, while the payload and subsystems are mounted on the experiment platform at the centre.

Figure 3. Drop test of Probe in descent configuration, with drogue parachute (photo courtesy of Martin-Baker Aircraft Co.)
6. Ocean impact

A landing of a space vehicle on an extraterrestrial hydrocarbon ocean is indeed an exotic and imaginative scenario, but is by no means improbable. While such an event would be a first in space exploration, the problem of landing on liquids is a fairly familiar one in a terrestrial context.

Vehicle splashdown loads were first considered theoretically in 1929 (although there was some experimental work in the UK in 1919) by Von Karman, for the purpose of estimating landing loads on seaplane floats, but received detailed examination for the Mercury and Apollo Programmes. Two theoretical approaches are possible to estimate loads: one is to model the impacting probe as a source sheet in potential-flow theory, and compute the resulting pressure and flow distribution in the liquid; the other is to assume that the impacting probe becomes 'loaded' with a virtual mass of ocean, using more-or-less empirical factors.

The second method was found to give excellent agreement with results from scale-model and full-size impact experiments and, being considerably simpler than the potential-flow method, is used here. The method was also used to evaluate splashdown loads on the crew compartment of the Space Shuttle 'Challenger'.

Let us assume a mass $M_0$ for the Probe, and vertical impact velocity $V_0$. As it penetrates, it becomes loaded with a virtual mass $M_v$ of liquid, with the Probe/liquid ensemble moving at a velocity $V$. The virtual mass, which varies as a function of time, may be considered as the effective mass of liquid with which the Probe shares its momentum at a given instant.

Applying conservation of momentum and ignoring drag, weight and buoyancy forces (e.g. during the first 0.05 s of impact, weight would make only a 1% change in the Probe's momentum) gives

$$(M_0 + M_v) V = M_0 V_0$$

(1)

Differentiating,

$$(M_0 + M_v) \frac{dV}{dt} + V \frac{dM_v}{dt} = 0$$

(2)
The virtual mass \( M_v \) is usually taken as a fraction \( k \) \((0.75\) in Ref. 32 and \(2/\pi \)(\(=0.64\)) in Ref. 34: here \( k=0.75 \) is used) of the mass of a hemisphere of liquid with a radius \( R \) equal to that of the (assumed axisymmetric) body at the plane of the undisturbed liquid surface (Fig. 5). Thus, for a liquid of density \( \rho \), the virtual mass is

\[
M_v = 2k\pi \rho R^3/3
\]

For a general axisymmetric shape \( R=f(h) \), where \( h \) is the penetration distance, it is easy to show that

\[
\frac{dM_v}{dh} = 2k\pi \rho R^2 \frac{dR}{dh}
\]

noting that \( \frac{dh}{dt} = V \) and \( \frac{dV}{dt} = a \)

we obtain

\[
a = \frac{-V^2(2\pi k\rho R^2)}{(M_0+M_v)} \frac{dR}{dh}
\]

These equations are easy to solve numerically (indeed in the early days \(12 \) the numerical computation was performed manually). Terms for drag, weight and buoyancy could be added, but do not significantly affect the peak loads.

For a spherically-bottomed vehicle with a radius of curvature \( R_N \) and a penetration distance \( h \) (Fig. 5), this `waterline' radius is given simply as

\[
R = (2R_N h - h^2)^{1/2}
\]

and the equations can be solved analytically to derive (for example) the peak loads (see, for example Ref. 34).

The above method can also be used to estimate the loads on a 75 kg human diving into a swimming pool. If the nose radius corresponds to the size of the head, the peak load is a little under 1 g; if, on the other hand, the nose radius is increased to, say, 30 cm (i.e. a `belly flop'), the loads increase to \(~6\) g. This order-of-magnitude change in load is painfully apparent to those unfortunate enough to verify the nose-radius dependence experimentally!

---

**Figure 5.** Idealised geometry for a vertical impact of a sphere-nosed body into a liquid.
Figure 6a. Deceleration and velocity profile for the nominal impact case, assuming the Probe shape as described in the Appendix to be perfectly rigid (drag and buoyancy not modelled).

Figure 6b. Deceleration profile for the same impact case, but also showing the profile for a spherical nose radius of 650 mm for comparison (drag and buoyancy not modelled).

It is tempting to approximate the shape of the Probe with a sphere of 650 mm but, due to the sensitivity to nose radius, this might lead to underestimation of the peak loads. Figure 6 shows the acceleration versus time and speed versus time profiles for a 207 kg Probe splashing into liquid of density 600 kg m\(^{-3}\) for the actual Huygens Probe shape (see Appendix). A corresponding profile assuming a sphere of 650 mm radius is shown for comparison. It is apparent that the peak load is reached after about 0.01 s, after the Probe has penetrated to a depth of about 3 cm. After the peak, the loads decay away; after this, drag, buoyancy and weight begin to significantly modify the Probe’s motion, but this is not evaluated here.

(Note that there should be a slight jump in the acceleration level at about \(t = 0.1\) s as the bulky attachment mechanisms used to hold the front shield during entry hit the liquid, but this has not been modelled here).

The peak impact loads are shown in Figure 7 for the actual Huygens Probe shape with mass 207 kg for various impact velocities and ocean densities (pure liquid methane has a density of about 450 kg m\(^{-3}\), ethane about 600 kg m\(^{-3}\) and liquid nitrogen about 800 kg m\(^{-3}\)). The ocean compositions suggested in Reference 35 indicate the most likely density range as 600–650 kg m\(^{-3}\).

A method similar to that above can be used to estimate the loads on appendages, such as the booms of the Huygens Atmospheric Structure Instrument (HASI). First estimates suggest that the splash loads should generate bending moments at the boom roots of the order of 10 Nm, and so, provided the boom hinge attachments do not act as stress concentrators, the booms should survive.

It was found during tests on a 1/4-scale model of the Apollo Capsule™ that vertical landing loads are virtually independent of any impact-velocity component parallel to the surface. Additionally, impacts with the axis of the Capsule in a non-vertical orientation had lower accelerations (e.g. 60% of normal load for a 10° pitch at impact) than the nominal vertical case (intuitively we might expect this, as the interface of the spheroidal bottom of Apollo with the upper conical structure makes a ‘sharp’ corner which penetrates the ocean more easily than the ‘blunt’ bottom).

Thus, loads along the main axis of the Probe at impact are highest for vertical impact (the nominal case). The worst-case loads occur for a light Probe, high impact velocity, and dense ocean. These worst-case loads are about 13 g, assuming the Probe to be rigid; nominal loads are of the order of 9 g.

Tests on the Apollo Module™ showed that vehicles with non-rigid bottoms (such as Huygens) may experience peak loads approximately 50% in excess of those encountered with a rigid bottom, so perhaps a margin should be added to the above figures (in Ref. 36, for example, accelerations of 38 g were measured when calculations indicated a rigid-body value of 22 g). An estimate of the impact pressure on the Probe can be made by dividing the impact force (equals Probe mass times instantaneous acceleration) by the wetted surface area of the Probe. Ignoring the
singularity at the instant of impact, this pressure is of the order of 10−20 N/cm². Comparing this with the strengths of Probe elements (see Section 9 and the Appendix) indicates that the Probe will indeed deform, modifying the deceleration history given in Figure 6. No attempt is made here, however, to model the coupled flow/structural effects.

Since the Huygens Probe is designed for (axial) entry loads of the order of 20 g in any case, the axial loads for liquid impact should be perfectly survivable, even with a margin for non-rigid effects imposed on the splash load predictions. Note, however, that the entry loads are conducted to the experiment platform via a different load path, leading to compressive stress on underside units.

Should there be a sideways velocity component at impact, there will naturally be a sideways (radial) acceleration. This will be small, however, compared with the axial loads (in Ref. 36, for example, an impact with an 11° pitch angle, a 7 ms⁻¹ vertical velocity, and a 3 ms⁻¹ horizontal velocity had an axial load of 30 g, with a sideways load of only 2.9 g). The radial loads on the Probe are in effect in the same direction as the launch loads (the Probe is attached sideways to the Cassini Orbiter at launch), so that, given the anticipated impact conditions, sideways loads should not cause damage to the Probe. A sideways impact will also produce an angular acceleration pulse, but this is not considered further here.

After the initial acceleration pulse, the acceleration decays until the Probe’s entire lower surface is immersed. There will be a slight pulse due to liquid inertia loads on the radar altimeter antenna and the appendages used to attach the Probe to its entry shield. After this, however, the inertia loads are minimal and the forces of hydrodynamic drag and buoyancy are the most important. For the nominal (5.2 ms⁻¹) vertical impact with an ethane ocean (600 kgm⁻³), the Probe will have been decelerated to about 2.5 ms⁻¹ by the time its lower surface is completely immersed. Rough estimates suggest that the Probe will continue moving for another 1 s to a depth of about 1 m, with the top platform a few tens of centimetres below the depth of the ocean (the antennas should be submerged only momentarily, if at all). Buoyancy brings the Probe bobbing back up to the surface about 1.5 s after first contact. Note that the slightly lower impact loads and deeper penetration reported in Reference 7 were computed for a somewhat narrower Probe shape, before the current design had evolved.

In the event of a landing in a lake or sea, the subsequent dynamics and flotation characteristics of the Probe are of interest, since these will affect the post-impact scientific measurements.

A key question is naturally whether the Probe will float at all. Since the bulk density of the Probe is of the order of 200−300 kgm⁻³, while that of the ocean (assuming it is free of bubbles) is about 600 kgm⁻³, the answer is that it will. However, the level at which it floats is also of interest, to determine whether the Descent Imager and Spectral Radiometer (DISR) is above the ‘waterline’, and to verify that the measurement cavity of the Surface Science Package (SSP) is below it, so that its transducers are in contact with the liquid.

In order to determine the flotation level, a simple model (Fig. 8) has been set up to calculate the force and moment due to buoyancy for the Probe at any immersion depth and orientation. This is done simply by assuming that the Probe is axisymmetric, and breaking it down into small elements. Simple geometry determines whether each element is submerged or not; if submerged, it has a buoyant force equal to the weight of the displaced liquid. This force also has a moment arm associated with it. Summing these forces and moments allows the overall upthrust and torque to be determined. These quantities are given in Figures 9 and 10 for a nominal ocean density of 600 kgm⁻³; the forces and moments scale directly with ocean density.

It is seen, by comparing the upthrusts with the Probe weight (Fig. 9), that the Probe should float with the ‘waterline’ almost at the level of the Probe centre-of-gravity. Thus, happily, the DISR is above the surface, and the SSP cavity is filled.

7. Post-impact dynamics for liquid landing
As all the moments are negative, the Probe is stable in its nominal vertical attitude (assuming that it is not significantly deformed during the impact). It would need to be tilted to about 87° before capsizing, which is presumably only possible in the event of improbably high (>impact speed) surface winds.

These negative moments are, for small angles, approximately proportional to the angle of the Probe (Fig. 10). A 'rocking' period can thus be determined by assuming that the rocking is a simple harmonic motion. If the buoyant torque $J = UD = k\gamma$, where $\gamma$ is the angle of the Probe (Fig. 8), then the period of the motion is simply $2\pi\sqrt{(I/k)}$ where $I$ is the Probe's transverse moment of inertia. Further, since the constant of proportionality ($\sim 68$ Nm/rad for $D = 600$ kgm $^{-3}$) is itself proportional to the ocean density, and the Probe's orientation can be measured with tilt sensors (part of the SSP experiment), this leads to a crude method of determining ocean density. For a density of 600 kgm $^{-3}$, the rocking period is 3.4 s; for a 650 kgm $^{-3}$ ocean, the period is 3.26 s. Bobbing periods for vertical oscillations (since the upthrust is proportional to displacement) can also be established, and can be measured with Probe accelerometers to derive another, albeit coarse, density measurement.

In the event of landing in a lake or sea, the payload will be able to measure currents and wave properties, ocean composition, physical properties (e.g. dielectric constant, useful in interpreting radar data), turbidity, and depth. The DISR camera will be above the 'waterline' and will be able to image the surface and lower atmosphere. The detailed science plans for the surface are still under discussion (see later).
Impacts with solid surfaces are much harder to evaluate, due both to the paucity of experimental data and the difficult analytical treatment. A handful of drop tests onto sandy surfaces were performed in connection with the Mercury and Apollo programmes. In addition, a large series of experiments were conducted in connection with using penetrators to evaluate the lunar surface (before the Surveyor series of missions was performed). In these experiments, small dense ball-nosed vehicles were dropped or shot into a variety of materials including sand, earth, lead, balsa wood and concrete.

If the rock/ice at the landing site is finely-divided and non-cohesive (since it is so solid, we may perhaps treat it as sand (although it will have a lower density than sand, so predictions here will perhaps be slightly pessimistic). A formula developed in Reference 39 gives peak deceleration for nose diameter \( D \) (m), mass \( M \) (kg) and impact velocity \( V \) (m/s) as proportional to \( D^{1.0}V^{1.5}M^{-1.0} \). However, this empirical formula does not appear to scale well to the Apollo and Mercury results (see Table 2).

Reference 39 also gives some theoretical expressions for the impact of spheres into elastic ('The Hertz Law') and plastic ('The Meyer Law') materials which appear to scale with much more success to the other results. Since the Mercury and Apollo models are more similar in size to Huygens, and their speeds and masses are comparable, these results are the most pertinent to validating the estimation methods.

Expressions (7) and (8) below predict peak decelerations (assuming Huygens has a diameter of 1.3 m, and mass and velocity as in the previous sections) of 32 g and 28 g, respectively, for landing on sand surfaces.

The expressions given in Reference 39 depend explicitly on given material properties: in the expressions below, however, I have simply made an empirical fit to the data in Table 2. Thus the peak impact accelerations are given (in Earth g) as

\[
\alpha_{\text{max}} = 35 D^{0.2}V^{1.5}M^{-0.4} \tag{7}
\]

\[
\alpha_{\text{max}} = 60 D^{0.5}V^{1.6}M^{-1} \tag{8}
\]

Since the bearing stress in sand increases with depth (see later), Expression (7) is probably preferable on theoretical grounds. Additionally, it appears to give a marginally better fit to the (limited) dataset in Table 2.

Thus if Huygens can be considered as a rigid sphere of radius 650 mm, its peak impact deceleration on landing on sand (i.e. a moderately dense, non-cohesive fine particulate material, or regolith) should be in the range 26–32 g. The presence of larger lumps of material like boulders will, of course, modify this prediction (see, for example, Ref. 40).

This impact deceleration is rather larger than the entry deceleration, but perhaps within engineering margins. Consider, for example, the power distribution relays (Deutsch EL415). Sudden deceleration at impact could cause these to 'chatter', causing momentary interruption to the power supply. The 'all axes' acceleration specification is 15 g, but the shock (6 ms) tolerance is 200 g. For the Probe to stop with 30 g from 5.2 ms takes about 16 ms, and so one would cautiously expect that the specification should not be exceeded. However, the situation is marginal.

<table>
<thead>
<tr>
<th>Model</th>
<th>Ref</th>
<th>Peak load measured</th>
<th>Hertz law ( 35D^{0.2}V^{1.5}M^{-0.4} )</th>
<th>Meyer law ( 60D^{0.5}V^{1.6}M^{-1} )</th>
<th>Empirical (Ref. 39) ( 80D^{1.5}V^{1.5}M^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3-scale Phase-A Huygens</td>
<td>-</td>
<td>26</td>
<td>27.1</td>
<td>27.4</td>
<td>10.72</td>
</tr>
<tr>
<td>1/3-scale Phase-A Huygens</td>
<td>-</td>
<td>20</td>
<td>17.4</td>
<td>15.67</td>
<td>2.2</td>
</tr>
<tr>
<td>1/6-scale Mercury Capsule</td>
<td>38</td>
<td>70</td>
<td>102</td>
<td>103</td>
<td>106</td>
</tr>
<tr>
<td>1/4-scale Apollo Capsule</td>
<td>36</td>
<td>49</td>
<td>49.6</td>
<td>52</td>
<td>54.77</td>
</tr>
<tr>
<td>3-inch hemisphere</td>
<td>39</td>
<td>50</td>
<td>249</td>
<td>149</td>
<td>51.8</td>
</tr>
<tr>
<td>Huygens</td>
<td>-</td>
<td>77</td>
<td>31.6</td>
<td>24.7</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Table 2. Comparison of theoretical predictions of peak impact loads for sand impact with experimental data. Huygens model data are from unpublished work by A. Sciff of NASA Ames, using 1/3 and 1/9 scale models of the Phase-A Huygens Probe design.
Figure 11. Consequences of impact depend on relative strengths of landing-site material, subsystems boxes and experiment platform:
(a) soft material: becomes compressed
(b) hard material: loads applied to boxes, causing failure
(c) hard material: loads applied to boxes, punching them into honeycomb of experiment platform

9. Impact-dynamics model

All the above considerations assume the Probe does not deform. However, since the impact process leads to the application of structural loads directly onto units on the Probe's underside, these units may be deformed, leading to failure. Figure 11 indicates how the impact energy may be dissipated in the soil, the units, or the experiment platform. To examine in detail the structural effects of the impact on the Probe, and the sensitivity of the Probe deceleration history to surface mechanical properties, a more detailed approach is required.

The model considers the Probe essentially as a point mass, mounted atop several (seven in the nominal model) 'stacks', each of four elements (Fig. 12). Each element is defined with an undistorted length, and a stress vs. compression characteristic described by linear interpolation between four given points (Fig. 13). Each stack is allocated a cross-sectional area.

For example, one 'stack' represents the spacecraft batteries, and comprises the following elements: the experiment platform (a honeycomb sandwich), the batteries themselves (modelled as essentially rigid boxes), an airgap, and a layer of thermal-insulation foam. Note that although there are actually five batteries on the Probe, they are modelled (for speed) as one stack with an area equal to that of the sum of the actual battery boxes. The 0.8 mm aluminium fore-dome is treated separately in these calculations (see Appendix). It is assumed that the dome does not interact (i.e. exchange loads) with the stacks.

The impact simulation works as follows: starting from a given height above the surface (assumed flat), the program steps down in height increments of 1 mm (the height is defined from the upper side of the experiment platform to the undisturbed surface). The penetration of a given stack into the surface material is computed by subtracting the sum of the lengths of its elements (each multiplied by its own compression factor) from the height. The penetration yields a certain bearing strength (see Section 10). The program considers each element in turn, to determine which element is the 'softest' (i.e. yields the lowest compressive stress for the next height decrement), whether one of the stack elements or the soil itself, and allows this selected element to deform.

Figure 12. Schematic of crash model used in this study. Different box shadings indicate different element strengths.
As an element deforms, it resists more stress (typically), and thus is less likely to be deformed in the next iteration. Naturally soft elements (such as foam or airgaps) deform first, while stronger elements do not begin to deform until the loading on the stack becomes quite high (e.g., due to deeper soil penetration). The deceleration of the Probe platform is derived by summing the various loads and dividing by the Probe mass. Note that depth is the independent variable, not time. The simulation is stopped when the velocity falls to zero, giving the peak loads and depth of penetration.

The element lengths and stack areas are taken from Probe engineering drawings, and (for ACP, GCMS and SSP) from payload engineering drawings, and are summarised in Table 3. The methods used to estimate the stress-compression characteristics of the various elements, listed in Table 4, are described in the Appendix.

The program runs in a couple of minutes on a standard 386 PC; sample screen dumps are shown in Figure 14. The (quite primitive) numerical methods used in the program yield results accurate to about 10%. More accurate methods are not justified, given the overall simplicity of the model and the uncertainty of model parameters such as buckling stresses, etc.). Thus, while the model's results are useful in gaining a qualitative idea of what is happening (i.e., discriminating between the cases in

Table 3. Elements of Probe impact model: lengths are in millimetres, while stress/compression characteristics are given in Table 4

<table>
<thead>
<tr>
<th>Unit</th>
<th>Area (cm²)</th>
<th>Element 1 length/type</th>
<th>Element 2 length/type</th>
<th>Element 3 length/type</th>
<th>Element 4 length/type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSP</td>
<td>250</td>
<td>80 4</td>
<td>50 9</td>
<td>150 8</td>
<td>30 2</td>
</tr>
<tr>
<td>ACP</td>
<td>506</td>
<td>80 3</td>
<td>150 7</td>
<td>40 12</td>
<td>50 2</td>
</tr>
<tr>
<td>GCMS</td>
<td>302</td>
<td>80 4</td>
<td>80 5</td>
<td>60 6</td>
<td>50 2</td>
</tr>
<tr>
<td>BRTS</td>
<td>2625</td>
<td>80 3</td>
<td>150 10</td>
<td>40 1</td>
<td>50 2</td>
</tr>
<tr>
<td>PCDUa</td>
<td>1044</td>
<td>80 3</td>
<td>150 11</td>
<td>40 1</td>
<td>50 2</td>
</tr>
<tr>
<td>RADAR</td>
<td>295</td>
<td>80 3</td>
<td>110 10</td>
<td>50 1</td>
<td>50 2</td>
</tr>
<tr>
<td>PDCUb</td>
<td>1140</td>
<td>80 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 13. Stress-compression characteristics for four example elements from Table 4

ASA Journal 1994 Vol. 18
10. Surface models

Having established the structural properties of the Probe, it remains to obtain plausible, but usable, surface models to interact with it. A review of current understanding of Titan’s surface can be found in Reference 8. In principle, any surface type is possible, but only three principal types are examined, namely regolith, sludge, and hard ice/rock.

Since surface heat flow on Titan is sufficiently high that the crust may be convective, mountain-building and tectonics cannot be ruled out, and so the possibility of sloping terrain cannot be excluded. Similarly, aeolian transport of surface particulates could form dunes. However, for the purposes of this work, I assume that the impact occurs on flat, horizontal terrain.

Fresh, hard ice might exist where there has been recent cryo-volcanic activity, at the base of young impact craters, or where fluvial or aeolian activity has scoured the surface free of loose particulates. This may be modelled by setting the surface hardness to an arbitrarily large value.

Particulate material is likely to cover some, if not all, of Titan’s surface. This material would include solid photochemical aerosols (acetylene and higher organics) and icy impact ejecta. However, the mechanical properties of these deposits are not well-constrained. Dry deposits of aerosol particles (which appear to have a fractal
structure, judging from Pioneer 11 polarimetry and Voyager 1 infrared results, and
theoretical modelling) could be very soft, like fluffy snow. On the other hand, rainfall
or other processes could compact these deposits into much-harder soils.

A comprehensive soil-mechanics treatment would be impractical and so a simple
model is given here. Following Sperling & Galba, I use a soil stress \( \sigma \) of the form

\[ \sigma = k_1 + k_2 x + k_3 v^2 \]  

where \( \sigma \) is the force per unit area on the spacecraft, \( x \) is the penetration depth into
the soil, and \( v \) is the instantaneous impact velocity of the spacecraft. For all cases
examined here, \( k_3 \) is set to zero (as in Ref. 25). Note that in Reference 26, \( k_1 = 0 \),
and \( k_2 \) is called the ‘subgrade modulus’.

In order to obtain realistic figures for \( k_1 \) and \( k_2 \), data for a variety of terrestrial and
planetary surfaces have been collected in Table 5. These values, and their
Corresponding soil stresses from Equation (9), are used to select appropriate values for
use in the model. It is instructive to compare the soil stress at various depths with,
for example, the pressure on the sole of a shoe (say 1–2 N cm\(^{-2}\)).

As a result, the data in Table 5, the nominal ‘regolith’ model assumed in this
work is essentially that of the lunar soil as measured by Surveyor, namely \( k_1 = 1 \)
N cm\(^{-2}\), \( k_2 = 0.1 \) N cm\(^{-2}\) mm. A soft, fluffy aerosol deposit would have parameters
\( k_1 = 0, k_2 = 0.01 \) N cm\(^{-2}\) mm. As for wet mixes of aerosols ejecta with liquid ethane/methane, i.e. ‘sludge’, a
useful terrestrial analogue may be clay, at one extreme. The other extreme, naturally,
is thin sludge, which should be treated similar to a ‘pure’ liquid impact. Penetration tests on clay typically yield a constant ‘flow pressure’: i.e. \( k_1 = 0 \). Tests on sod (Ref. 39) found that a value of 37 psi, or \( k_1 = 25 \) N cm\(^{-2}\) gave a good fit to data, so sludge
models in this study have \( k_1 \) values around, or lower than, this.
11. Model results

Some useful comparisons with the rough estimations in Section 8 can be made by setting the stiffness of all Probe elements to large values (i.e. forcing the Probe to act like a ‘rigid body’). For the nominal regolith model ($k_1=0.1$ N cm$^{-2}$, $k_2=0.1$ N cm$^{-2}$ mm$^{-1}$) the peak acceleration obtained is 28 g, reassuringly in the estimate range of Section 8.

With the Probe structural strengths set as in the Appendix, and Tables 3 and 4, the peak acceleration is 23.4 g. Varying the impact velocity from 4.6 to 5.8 ms$^{-1}$ yields peak accelerations of 19.6–27.4 g.

The deceleration history for the nominal Probe strengths, but various soil properties, is given in Figure 15; Figure 16 shows the dependence of the peak load on soil hardness.

If the ground is made very stiff (i.e. generates extremely large bearing strength for minimal penetration, by setting $k_2$ to very large values), the peak load is determined by the stiffness of the Probe elements alone. It was found that loads were >100 g, and significant crushing of most of the Probe elements occurred. Thus, impact on an arbitrarily hard surface would lead to failure of the Probe.

Table 6. Peak accelerations, and loads on individual Probe units, for various soil strengths

<table>
<thead>
<tr>
<th>Soil stiffness $k_2$ (N cm$^{-2}$ mm$^{-1}$)</th>
<th>Peak deceleration (g)</th>
<th>Load on GCMS (kN)</th>
<th>Load on SSP (kN)</th>
<th>Load on ACP (kN)</th>
<th>Load on PCDU box (kN)</th>
<th>Load on radar box (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>11.6</td>
<td>.95</td>
<td>.83</td>
<td>1.6</td>
<td>5</td>
<td>0.8</td>
</tr>
<tr>
<td>0.1</td>
<td>25</td>
<td>3.6</td>
<td>3.6</td>
<td>7.0</td>
<td>19</td>
<td>3.4</td>
</tr>
<tr>
<td>1</td>
<td>35</td>
<td>7.6</td>
<td>6.5</td>
<td>21</td>
<td>28</td>
<td>8.6</td>
</tr>
<tr>
<td>10</td>
<td>40 (41)</td>
<td>7.6 (7.9)</td>
<td>8.2 (8.3)</td>
<td>23 (25)</td>
<td>31 (32)</td>
<td>13 (13)</td>
</tr>
<tr>
<td>100</td>
<td>79 (75)</td>
<td>8 (45)</td>
<td>32 (32)</td>
<td>75 (75)</td>
<td>42 (0.2)</td>
<td>12 (0.1)</td>
</tr>
</tbody>
</table>

Figures in parentheses refer to the case where the GCMS mounting is deformed 'normally', without the GCMS being removed from the model when its load exceeds 8 kN.
For the nominal Probe model, landing onto regolith, the peak deceleration is marginally above the entry g-load. Some slight deformation of the GCMS and PCDU occurs, and the experiment platform above the SSP and GCMS is somewhat deformed. Nevertheless, at least partial Probe operation after such an impact seems likely.

For heavy sludge impact, the partitioning of loads is less effective than for regolith and so the GMCS and its attachment to the experiment platform would be damaged, with the ACP and SSP also receiving large loads. However, the Probe stops sufficiently quickly that loads are not applied to the PCDU box, so that survival of the Probe (and topside experiments such as the DISR) is still probable.

Landing on fluffy aerosols \((k_1=0, k_2=0.01)\) leads to modest g-loads, and very little deformation of the Probe. However, the Probe does penetrate deep enough for the sensor head of the DISR to be buried, compromising post-impact imaging.

The caveat mentioned in Section 9 is repeated: while the depth of penetration and deceleration histories predicted by the model are probably representative, the structural results for individual units should be trusted only qualitatively.

For a scientific data return post-impact, one or more of the experiments must survive the impact, the power system must remain operational, and at least one of the redundant data-handling and transmission chains must function. An additional aspect is that the attitude of the Probe must be such as to keep the orbiter spacecraft within the antenna lobe to keep the radio link open. As the Huygens Probe is relatively flat-bottomed, this is quite probable. Furthermore, the link is guaranteed for Probe attitudes up to \(10^\circ\) from normal, so for shallow slopes at least (and surfaces with 'shoulders' of the order of 20 cm) the attitude of the Probe should not be sufficiently perturbed to break the link: without knowledge of Titan's topography, it is impossible to assign probabilities to this (see Ref. 50 for an approach where topography is known). Should there be a significant horizontal velocity component at impact, the Probe could also roll.

Other aspects vital to Probe survival (e.g. thermal environment) are unlikely to be dramatically altered at impact (although the performance of the insulating foam will be degraded by crushing). The mission energy and link budgets are guaranteed for a minimum of 3 min after impact but, depending on the exact descent location (which affects the time-above-horizon and link margin of the radio link to the Cassini Saturn Orbiter) and spacecraft performance in terms of energy utilisation, could permit a somewhat longer surface mission, of perhaps 30 min or more. Thus impact damage is probably the main constraint on surface operation. As for the experiment payload, the Ultra-Stable Oscillator for the Doppler Wind Experiment, the Huygens Atmospheric Structure Instrument, and the Descent

12. Probe survival and post-impact science
Imager/Spectral Radiometer are all on the upper side of the experiment platform, as are the electronics for the Surface Science Package. These elements (including the accelerometers which will measure the impact accelerations, and may subsequently search for seismic activity) should be safe from impact damage by crush loading.

The Aerosol Collector/Pyrolyser (ACP) is mounted on the lower surface, but has completed its mission well before impact. The ‘TopHat’ sensor accommodation structure of the Surface Science Package is made of glass-fibre panels and insulating foam. In the event of an impact with a hard surface, the TopHat will probably break, although the individual sensor subsystems may still function (in any case, most of these sensors are optimised for liquid surfaces, so the science loss in this scenario is small). The Gas Chromatograph/Mass Spectrometer is a long cylindrical instrument and projects from the base of the Probe through the experiment platform. A hard impact will probably crush the inlets of the instrument, although some instrument operation may still be possible (the inlets are heated to volatilise surface material for analysis); extreme loading would punch the GCMS through the experiment platform.

Thus a reasonable portion of the payload should remain operational after impact on a solid surface, in particular the Descent Imager/Spectral Radiometer, on the upper part of the spacecraft, which will be able to return images (using its side-looking imager) and spectra from the surface. Additionally, upward-looking photometric sensors on this instrument will be able to measure any impact-generated dust cloud (see later). A group has been set up within the Huygens Science Working Team (HSWT) to consider the measurements that are expected (or should be aimed for) post-impact.

13. Impact-dynamics measurements

The impact decelerations of Huygens will be recorded by the accelerometers of the HASI experiment (three-axis piezoresistive, with a force-balance ('servo') accelerometer along the vertical axis, all mounted near the Probe centre of gravity, and by a piezoelectric accelerometer in the SSP electronics box, about 20 cm from the Probe axis. Since both the SSP and HASI are on the upper side of the experiment platform, they should measure accelerations similar to those predicted by the model (i.e. they are in the same location as the 207 kg mass in Figure 12). Combining the data from both sensors should allow the elimination of structural oscillations generated by the impact.

As seen from Figure 7, the peak deceleration is a possible way of measuring ocean density. However, given the uncertainty in Probe structural effects and the presence of various appendages, etc. on the fore-dome, it should probably not be relied upon. The bobbing/rocking periods described in Section 7 may be better in this respect. In any case, ocean composition will be measured directly by the GCMS, and by inference from physical-properties measurements (refractive index, speed of sound, density, etc.) on the SSP.

The impact deceleration for landing on solid surfaces is strongly dependent on soil hardness. From the peak load alone it is not possible to discriminate between high-$k_1$ and high-$k_2$ materials, although the combination of the two (e.g. $k_1+50 k_2$ is a measure of the average bearing strength in the top 10 cm of soil) does show a broad correlation with peak load (Fig. 16) for weaker soils. However, examining the acceleration-time profiles (Fig. 15) shows that high-$k_1$ materials (sludge) have a much faster rise-time than high-$k_2$ materials. It is possible to discriminate sludge from liquids because, although their rise times are similar, the peak load for sludge is higher. Further investigations with the model will explore the sensitivity of acceleration profiles to surface properties, and variation of the stiffness of Probe structural elements.

It is probably impossible to discriminate from accelerometry between coarse and fine-grained soil deposits and, for that matter, determine soil stiffness for hard soils. However, there is a small impact sensor or 'penetrometer' that forms part of the University of Kent's Surface Science Package (SSP), comprising a small (14 mm diameter) force transducer mounted on a short mast projecting from the bottom of the Probe. The force profile measured by this instrument (over a much shorter time scale,
and thus corresponding to a much smaller spatial scale) should give an indication of particle size in the range 4–25 μm, discriminate between cohesive and non-cohesive surface materials, and give a better indication of soil stiffness for regolith and harder soils.

Identification of particle size would provide an indication as to whether the surface materials at the landing site had been sorted by aeolian or fluvial processes. For example, pyroclastic fall deposits (tephra) from terrestrial volcanoes often display a single central peak in a grain-size histogram due to ‘winnowing’ by wind as the eroded material falls back to Earth.

Following the landing of spacecraft on Venus and Mars, optical measurements have indicated the generation of dust clouds. These have been thrown up owing to the interaction of the aerodynamic wakes of the Venera and Pioneer Venus probes and the retro-rockets on the Viking spacecraft. Calculations of the mass and momentum in the aerodynamic wake of Huygens, and a comparison of the terminal descent velocity of dust particles on Mars, Venus and Titan, suggests that a similar phenomenon may occur at the Huygens impact.

Generation of a dust cloud implies that material at the landing site is fine and non-cohesive. Efforts to measure the particle size on the basis of opacity history (i.e. decay time) of the dust cloud have been relatively unsatisfactory, as the interaction of the wake with the ground is complex. However, recent theoretical and experimental investigations of the associated fluid-dynamics processes (e.g. the wake of a decelerating disk is of interest for the sometimes catastrophic ‘wake melt’ problem in parachute dynamics where the wake catches up with a decelerating parachute and causes it to deflate) show promise that, by the time Huygens reaches Titan, interpretation of dust-cloud data should yield better results.

A significant complication for Huygens is the fact that the parachute is still attached: it may be difficult to discriminate a drop in ambient light due to a dust cloud from that due to the parachute.

Simple analytical expressions have been presented for estimating the impact decelerations when landing space probes onto liquid and solid (particulate) surfaces. While necessarily limited in utility, these expressions are convenient ‘rules of thumb’.

A modest numerical model has been presented to make more accurate predictions of the Huygens impact-deceleration history for impacts onto solid surfaces. This model has enabled the investigation of the sensitivity of impact deceleration to surface mechanical properties, and the estimation of the Probe’s deformation during the impact.

These studies, and analogy with the Pioneer Venus and other missions, lead us to be cautiously optimistic about the prospects for a productive scientific return from the surface of Titan. Additionally, measurements of the impact deceleration and any impact-induced dust cloud will make modest, but useful, contributions to our knowledge of the physical state of Titan’s surface.

The author acknowledges the support of the ESA Huygens Project, and a postgraduate research grant from the UK SERC/PPARC. Some early parts of the work reported here were conducted while the author was a Young Graduate Trainee in the Huygens Project Team (YPY) at ESTEC in 1990/91.

Useful insights into crash-dynamics analysis techniques for aerospace vehicles were gained by a visit to the Cranfield Impact Centre Ltd., and fruitful discussions there with Dr Sadeghi and his colleagues. B. Steckemetz, of OHB System (Germany) helpfully provided details of the ESA Mars Lander study.

A. Seiff of San Jose State University (USA) is thanked for providing unpublished model impact data. J. Underwood of Martin Baker Aircraft (UK) is thanked for providing Figure 3.

14. Impact-induced dust clouds

15. Conclusions

Acknowledgements
The review of an early version of the paper by J-P. Lebreton of ESA Space Science Department is gratefully acknowledged, as are useful discussions with members of the Huygens Science Working Team, in particular T. Owen and J. Lunine.

The author thanks the following individuals for their cooperation in providing information on the Huygens Probe, payload and components: D. Wyn-Roberts (ESTEC, NL), M. Bannister (RAL, UK), J-F. Brun and M. Tintignac (CNRS, France), A. Nairn (ETCA, Belgium), C. Lewis and S. Way (GSFC, USA) and J. Underwood (Martin Baker, UK).

References

Appendix

Shape and Strength of Probe Shell

The Probe shape used in this study for the liquid-impact and post-impact dynamics is that of the outer aluminium shell, and is taken from Aerospatiale drawings. Essentially it is a dome with radius of curvature 1.25 m, until 15 cm along the probe’s central axis, when it becomes 15 cm, to meet a short cylindrical section (height ~7 cm, diameter 1.3 m) which corresponds to the location of the experiment platform. For about 30 cm above this, the shell is conical, meeting the flat top platform of 1.1 m diameter.

The various appendages (attach mechanisms, HASI booms, radar-altimeter antennae and the DISR) are not considered.

For the impacts with a solid surface, the contact area with the soil is computed by assuming the fore dome is an ellipsoid of revolution, with major and minor axes equal to the diameter and height of the actual shell.

Calculation of the force/deformation characteristics of even a simple shell is difficult (see, for example, Ref. 61) and so it has been assumed here that the shell obeys a linear force/deformation law. Thus, the force on the shell is directly proportional to the distance between the surface and where the shell’s apex would be had it not been deformed, except where this force is more than the surface bearing strength multiplied by the contact area, in which case the shell force is set to be the latter.
In the nominal model, a shell force constant of 1000 N/m has been used. A
investigation of various impact cases suggests that the impact deceleration history is
relatively insensitive to variations of one order of magnitude in this parameter. In this
case, the work done in deforming the shell is only about 2% of the impact kinetic
energy.

Estimation of Structural Characteristics of Probe Underside Units

Detailed study of each individual unit could yield accurate stress/compression
relations. However, this would be impractically labour-intensive, and difficult to
justify given the uncertainties elsewhere (e.g. in the soil models, impact orientation,
etc.). Thus what follows is a set of engineering estimates, using rules-of-thumb, to
generate first-order guesses for the response of individual elements. The loads and
stresses calculated by the model are only modestly sensitive to variations in
individual element properties; the overall validity of the 28 elements should be
adequate. Consequently, it is hoped that the results of the model are believable.

Only the aluminium fore-dome, parts of the insulating foam, and exposed
structural components will be chilled to ambient temperature (94 K), and so the
engineering properties assumed here are the room-temperature values, obtained from
standard data books, except where indicated otherwise.

Air gaps have essentially zero bearing strength until their compression exceeds
5% when the strength is increased to transfer loads to other elements.

Foam layers have a modest initial stiffness, readily deforming to about 50%
compression, and then bearing strength rises sharply. The points used to define the
stress-compression characteristic (Fig. 13) were taken from Figure 8 in Reference 62.

The honeycomb sandwich of the experiment platform takes a fairly large loading,
until the 'punch-through' threshold of 51 N/cm² is exceeded. This value was
supplied by CASA, contractor for the Probe's inner structure subsystem, via
Aero-SPATIAL and the ESA Project Team. The overall response shape (Fig. 13) was
not as resemble that of the aluminium footpads of the Surveyor spacecraft.

Note that for some units (SSP and GCMS) the platform area that supports the unit
is smaller than the area used to compute the soil loads: e.g. the GCMS is a 9-inch
diameter cylinder, with an effective soil penetration area of 300 cm² (its end is
flanged and has a circular inlet flange), but is only held by a support ring of area
- 60 cm² bolted to the platform. Consequently, the failure stress used in the
model for the honeycomb element in these stacks is modified by the ratio of the
areas.

Unit boxes are assumed to be relatively rigid, with a slight deformation due to the
uniform bending of the loaded face (using relations from Ref. 61), until a fail stress
is reached, estimated by multiplying the yield stress of the box material (assumed
glass-fibre-reinforced plastic for SSP, magnesium alloy for the PCDU box, and
aluminium elsewhere) by the cross-sectional area of the box walls (and any
reinforcement parts). Note that all the box units are sufficiently squat that yield
fracture occurs before an Euler buckling stress is reached. Additional justification for
this approach is the equivalence of experimental loads measured during the collision
crushing of a box-beam section, finite-element analysis of the same case and the
yield load computed as above. Since the boxes are not empty, however, a change of
stress is assumed to occur as compression continues and the internal components are
pushed together.

Some elements (e.g. the batteries) are considered rigid (i.e. their stiffness is
considerably larger than that of the other elements).

Manuscript received 22 April 1994