Lander Shock-Alleviation Techniques

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Future European space missions have been and are being discussed which involve the landing of scientific payloads on the surfaces of planets or comets in the Solar System, including Mars, Titan, the Moon and smaller remote comets. For all of these missions – Marsnet, Intermarsnet, Ares, Rosetta, Euromoon, etc. – the landing subsystem is a critical element in that a single-point failure could jeopardise the success of the whole mission. Several studies have therefore been performed to investigate potential landing devices and strategies, including the descent, impact, and post-impact stability and operation phases. They have shown that the acceleration peaks transferred to the lander structure during impact can be significantly higher than expected, resulting in major risks to the integrity of the scientific payload. This article reviews work that has been performed in this domain as part of the Agency's Technology Research Programme (TRP).

Introduction

The goal of the recently completed "Lander Shock Alleviation Techniques" TRP study was to identify, analyse, manufacture and test shock-alleviation devices capable of limiting impact loads to well-defined levels. It covered the overall landing subsystem as well as specially adapted support devices for sensitive equipment and payloads. Two types of landers were considered, namely hard- or penetrator-landers, and semi-hard landers, and prototype shock-alleviation components have been manufactured for both types.

Typical shock-alleviation requirements are first reviewed and a brief survey of shock-alleviation technology is presented. Dynamic analysis has been applied to investigate the shock loads on landers and their platforms and the effectiveness of the various shock-alleviation techniques that are available. The results are presented below, together with details of the conceptual design, manufacture and testing of the various prototype devices that have been devised.

Shock-alleviation requirements for space missions

Penetrator-landers

Penetrators of various types have been proposed for several missions to planets and other bodies within our Solar System, including the Moon (Lunar-A mission), a comet (Rosetta mission, although use of a penetrator is now doubtful) and Mars (Marsnet and Intermarsnet missions). In each case, the proposal involves a penetrator impacting with sufficient energy to enter the target surface and subsequently undertaking scientific measurements. Scientific instruments installed on or within these penetrators must survive and operate after being subjected to very high deceleration loads, ranging from 100 to 100 000 g depending on the type of surface being impacted, the type of penetrator and its impact velocity and orientation.

To provide a baseline for investigating shock-alleviation devices suitable for protecting sensitive scientific payloads, four existing designs of penetrator probe - for NASA's Mars Penetrator, the Russian Mars'94 mission, and ESA's Rosetta and Marsnet missions - were first reviewed. Each penetrator was assessed against its own particular mission requirements, in terms of impact velocity, deceleration loads, scientific goals and operational lifetime.

For the Marsnet Penetrator Lander (Fig. 1) which had been studied previously by ESA, the

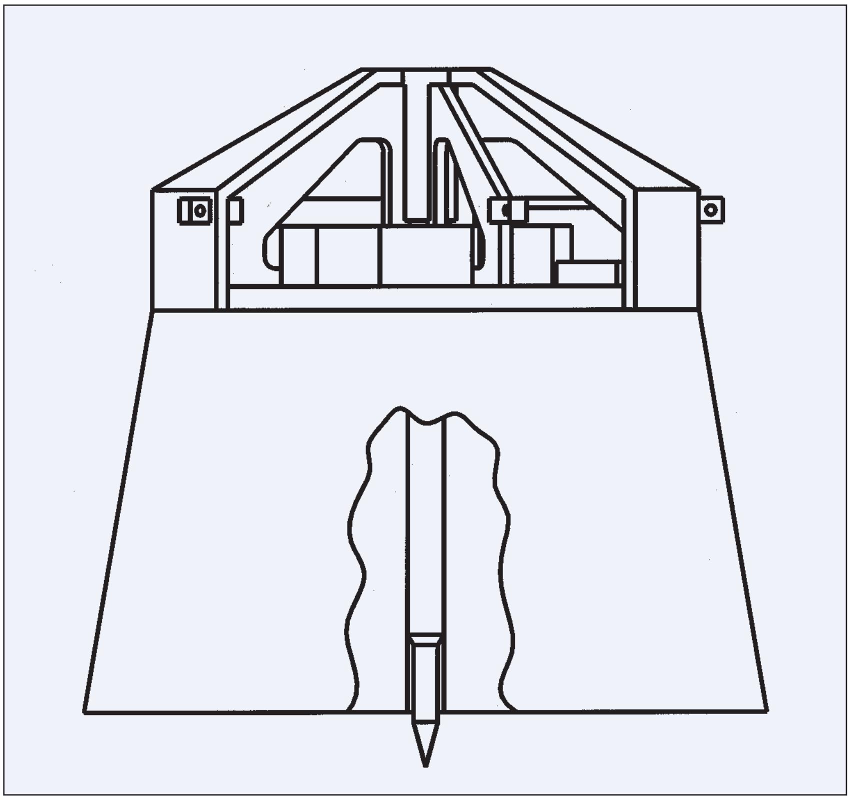


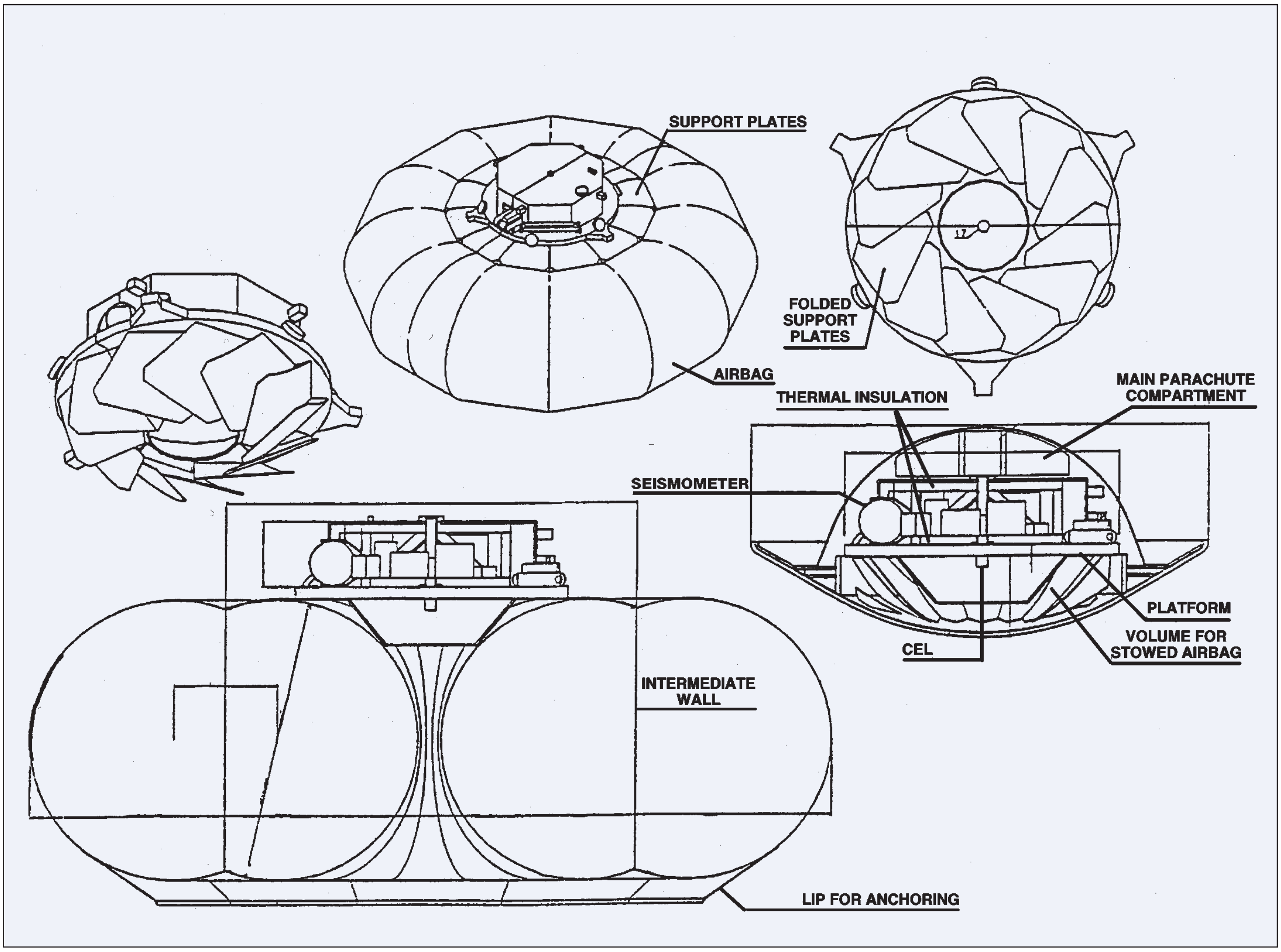
Figure 1. Marsnet penetrator-lander

Figure 2. Marsnet semi-hard lander

main performance requirement was to provide a safe and stable platform for the payloads and equipment throughout the impact/penetration process, without exceeding instrument loadings of 700 g. That penetrator is 0.94 m long, with an initial diameter of 0.04 m, expanding to 0.06 m. The diameter of the equipment platform to be shock-protected is 0.90 m. At impact, with a velocity of 70 m/s, the penetrator itself can experience impact loadings of the order of 5700 g, whilst the equipment platform loads are limited to 700 g through the crushing of an aluminium-honeycomb skirt. The time history of shock pulses on the platform approximate to a half-sine pulse with an amplitude of 700 g and a duration of 15 ms. Very sensitive payloads (e.g. cameras) can only withstand about 500 g. It was therefore assumed that the baseline shock-sensitive item would have a mass of 0.6 kg and could be expected to withstand a shock loading of 500 g applied over a period of 15 ms.

Semi-hard landers

Planetary and comet lander missions using low and medium impact velocities - namely Surveyor, Viking, Rosetta and Marsnet - have also been reviewed to establish a set of typical



requirements. These semi-hard landers do not penetrate the planetary or cometary surface.

The semi-hard lander designed for Marsnet (Fig. 2) has a diameter of 1.2 m and a height of 0.9 m. Its impact velocity is about 25 m/s in the vertical direction, and 0 to 25 m/s in the lateral direction. Overall shock alleviation is performed by an airbag system. The composition of the scientific payloads is similar for all of the soft and semi-hard lander missions, allowing a “typical” payload to be defined, with dimensions of 100x100x100 mm^3 and a mass of 0.7 kg. The maximum allowable deceleration has to be less than 100 g for shock-load inputs composed of long (5 ms) and short (0.5 ms) half-sine pulses with amplitudes of up to 200 g.

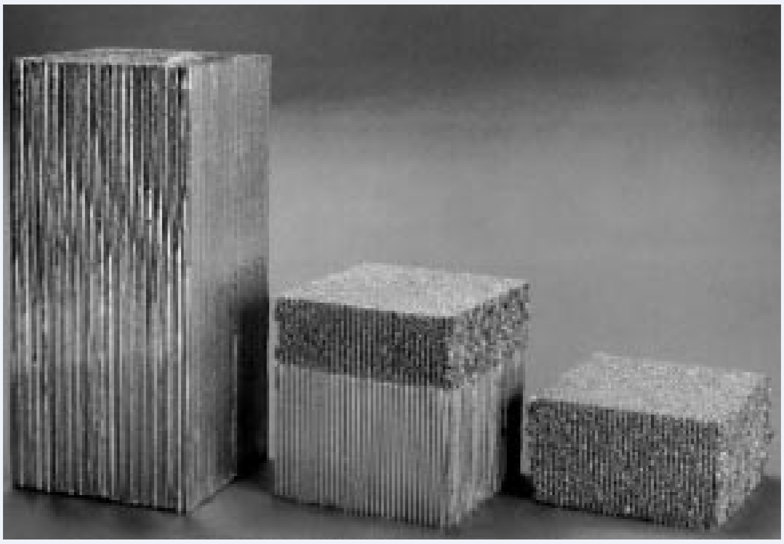
The shock-alleviation device also has to be as small as possible, whilst still maintaining a high functional reliability. There are additional requirements associated with the re-alignment and re-positioning (angular accuracy 1 degree, lateral accuracy 1 mm) of particular payload items such as cameras.

Review of shock-alleviation technology

The types of shock alleviation/absorption techniques that have been reviewed can be divided into devices based on friction and damping, devices based on irreversible deformation, and strategies to reflect shock waves by transmission control.

Among the first type, spring-damper shock isolators and fluid- or gas-filled telescopic dampers have been assessed. Standard metal-wire or elastomer shock isolators meet most of the specifications, but involve excessive elastic displacements because a very low stiffness is required to isolate against low-frequency shock loads. Assuming the use of an airbag landing system for the overall lander, telescopic dampers may be considered for the shock attenuation systems for the individual equipment or payload items mounted on the lander platform. However, the strong temperature dependence (density, pressure and viscosity) of fluid- or gas-based systems makes it difficult to specify critical design parameters such as valve diameters and outlet pressures sufficiently accurately to achieve a safe device. Also, telescopic dampers are usually both bulky and heavy.

Shock-alleviation devices based on irreversible deformation offer the highest specific energy-absorption capability, and crushable aluminium honeycombs and foams, as well as deformable tubes, have been reviewed. When loaded axially, aluminium honeycombs deform permanently in a highly controlled and predictable manner. As shown in Figure 3, as the peak compressive load is overcome, crushing at a constant level is maintained until the material “blocks”, forming a solid element. The area under the curve equates to the amount of energy that is dissipated. The manufacturers quote honeycomb crushing strengths only for static crushing and we therefore included dynamic tests in our study.



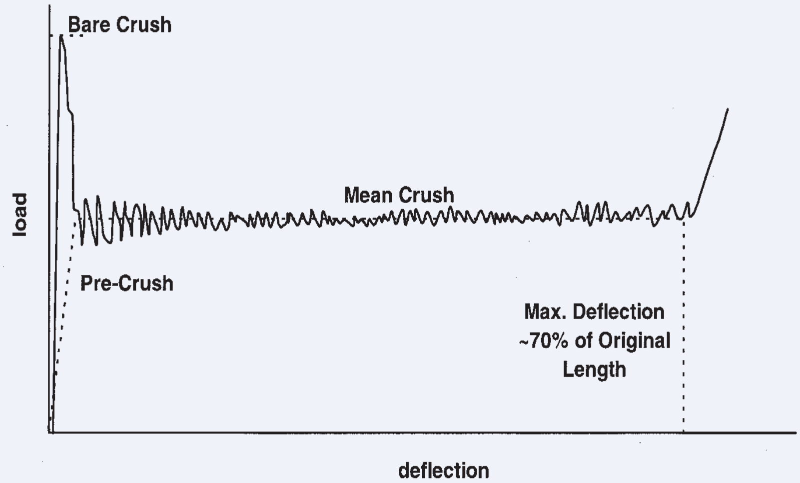


Figure 3. Crushing of aluminium honeycombs

Aluminium honeycombs possess a very low mass density (16-150 kg/m^3) and can be plastically compressed to 80% of their initial length (max. 70% without blocking). Compression strengths range from 0.35 to 17 MPa, and for pre-crushed honeycombs (avoiding the initial peak load) from 0.17 to 7 MPa. The resulting specific energy absorption is up to 30 kJ/kg. The major disadvantage of honeycombs is their dramatic strength decrease when loaded outside the honeycomb cell axis.

Aluminium foams can be produced with various mass densities, depending on the manufacturing process (Fig. 4). The lightest foams (so-called “M-type”) are made by injecting gas into molten aluminium-alloy material. They have densities ranging from 70 to 550 kg/m³ and compression strengths from 0.05 to 8 MPa. Foams made from aluminium powder (“P-type”) exhibit better homogeneity, but also have higher densities (300 to 1200 kg/m³) and compression strengths (2 to 25 MPa). Their specific energy absorption is lower than for honeycombs, and unlike honeycombs structural foams are effectively isotropic, exhibiting the same deformation behaviour regardless of the direction of the applied load.

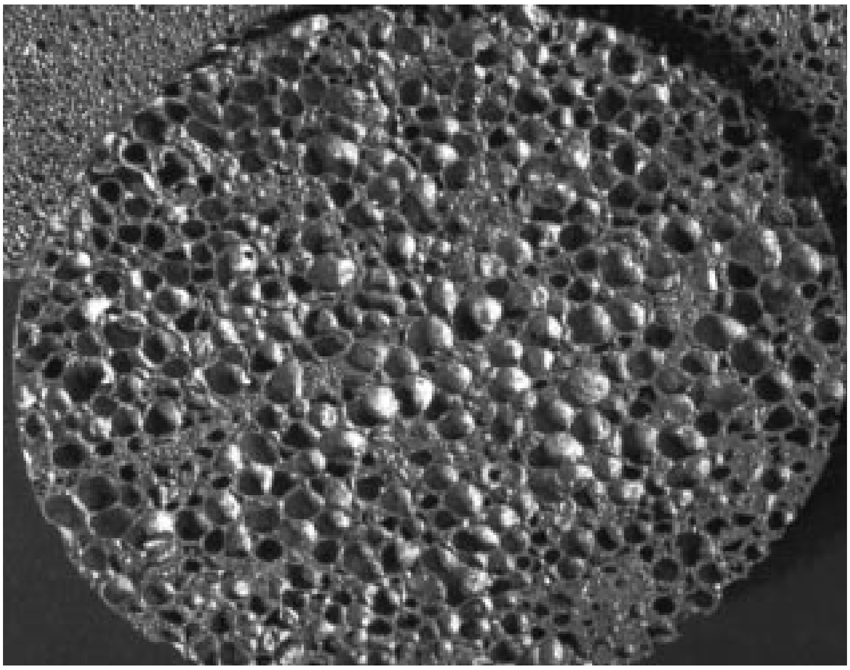


Figure 4. Aluminium foams

Deformable tubes (e.g. fragile or collapsible tubes, or tubes expanded by oversized steel balls) have been used in the aerospace industry for many years, but they too only work effectively in a clearly defined axial direction. Scaling down of the results in the literature for their application to a lander platform appears difficult.

Wave transmission control is only feasible as a means of shock alleviation within the dimensions of penetrator or semi-hard landers for the very high frequency range, whilst the predominant shock loads in the present case are quasi-static with significant contributions up to 1000 Hz.

Of the available shock-alleviation technologies for a penetrator-lander, therefore, the aluminium-honeycomb materials offer the best potential, provided due regard is paid to the need to include some form of guidance system to eliminate any unstable lateral collapsing that could otherwise occur. Tests with aluminium honeycombs and aluminium foams were therefore performed for the semi-hard lander.

Dynamic analysis of shock loads and shock propagation

Penetrator-lander

Finite-element and lumped-mass models have been used to predict the body loads for specific penetrator-lander impact conditions. These models were refined to enable reaction loads to be predicted at various locations, and in particular at the proposed baseline equipment locations on the payload platform. A simplistic model was then validated against the more detailed structural representations, prior to being used for parametric investigations of equipment shock-alleviation devices.

The body loads were computed using the baseline impact conditions defined in Figure 5. The simplified impact model was created using the lumped-mass code ISIM, in which the skirt crush characteristics were based upon static compression tests on a coupon sample (100x100x150 mm³) of aluminium honeycomb (HEXCEL 1/4-5052-0.0007) and were incorporated into the model as a non-linear general crushing curve, allowing hysteretic loading and unloading conditions to be handled. A vertical impact velocity of 70 m/s was applied to produce the penetrator-lander body response. The results show that at this velocity the skirt has sufficient energy-absorption capacity not to induce blocking, and not to exceed the baseline load limit of 700 g.

The baseline impact envelope was defined as approximating to a half-sine pulse of 700 g amplitude with a duration of 15 ms, which correlates well with the vertical impact response predicted by analysis.

Impact loads on payloads have been predicted using an extended lumped-mass model, including a payload placed on a crushable honeycomb cushion. Even when constraining the length of the shock-alleviation system to within the equipment platform, a load limitation of 500 g is feasible. Further attenuation of the equipment deceleration loadings requires an increase in the stroke distance by extending the attenuation device through the equipment platform and into the volume of the main honeycomb skirt (Fig. 6). The corresponding acceleration profiles show that with the extended protection device, the shock load on the equipment can be limited to 400 g (Fig. 7).

Semi-hard lander

A PATRAN/NASTRAN software package finite-element model of the Marsnet Semi-Hard Lander was used to determine typical shock loads on the lander platform and transform them into standard load cases. Parametric investigations were then carried out with simplistic models. Linear spring-damper isolators can be studied using the shock response spectrum tool within NASTRAN. The nonlinear material behaviour of energy-absorbing media such as aluminium honeycombs or foams is represented by plastic material models in the ABAQUS software package. This finite-element package can also be used for basic shock-wave propagation analysis.

Both vertical and oblique landing cases were analysed, and worst-case loads at various points of the lander platform were identified. The common characteristics of these loading time-histories can be represented by four basic load cases for the semi-hard lander:

Load case 1: Half-sine wave, 0.5 ms duration, 200 g peak
Load case 2: Half-sine wave, 5.0 ms duration, 200 g peak
Load case 3: Single long pulse (load case 1), followed by three short pulses (load case 2)
Load case 4: Similar to load case 3, but short pulses reduced to 120 g peak.

Load cases 3 and 4 were predominantly used in the analysis, whilst the final prototype tests were carried out with load case 2.

Analysis of spring-damper shock isolators using shock response spectra and time-history simulations clearly showed that the effective elastic displacement range is some centimetres, which exceeds the specifications of commercially available elements.

Using ABAQUS, combinations of absorbers, spring and damper elements were investigated using simple lumped-mass models. The irreversible crushing behaviour of honeycombs and foams was modelled using the ABAQUS features for ideal elastic/plastic behaviour. During the conceptual design phase, this approach was extended by introducing isotropic hardening to account for the blocking behaviour of the crushable elements.

Our analysis showed that aluminium honeycombs and foams are promising candidates for energy absorption. Single absorbers used for shock alleviation of a rigid payload are able to guarantee the 100-g acceleration limit with resulting crush strokes of 10 to 20 mm and negligible elastic motion. Structural damping has to be considered as a parallel load path entailing lower absorber crush levels and higher corresponding crush lengths. Series and parallel connections of absorbers with spring-damper elements show worse performances than single absorbers in

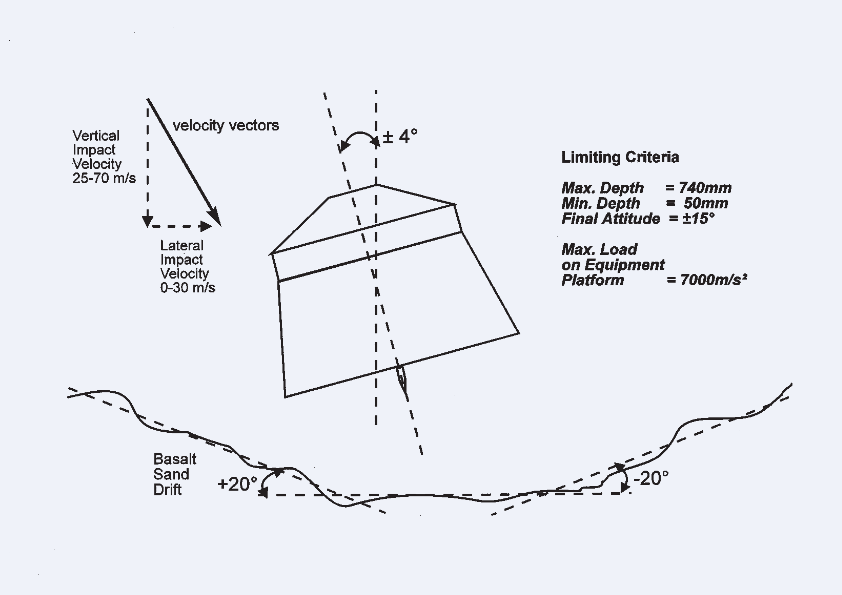


Figure 5. Baseline impact criteria for the penetrator-lander

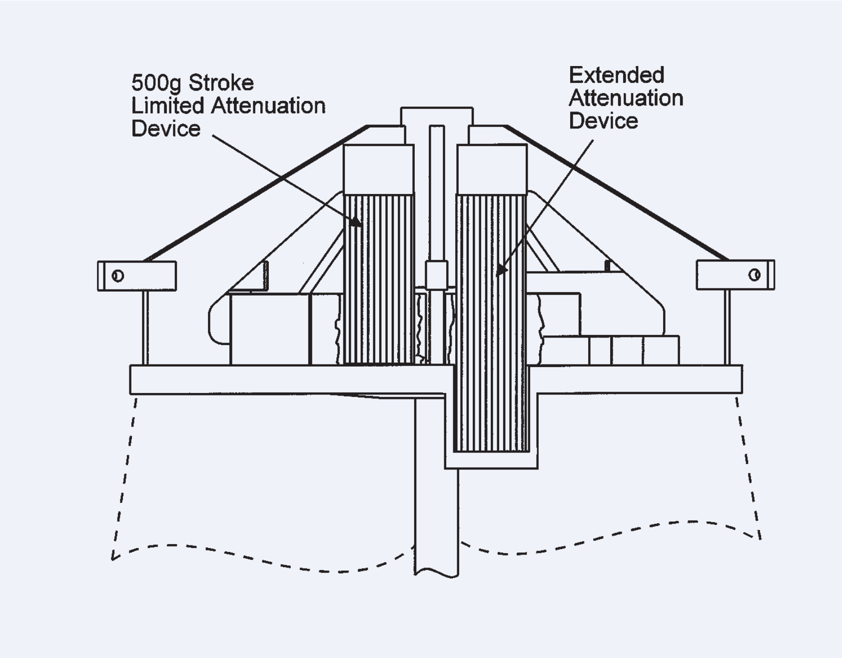


Figure 6. Incorporation of extended attenuation device

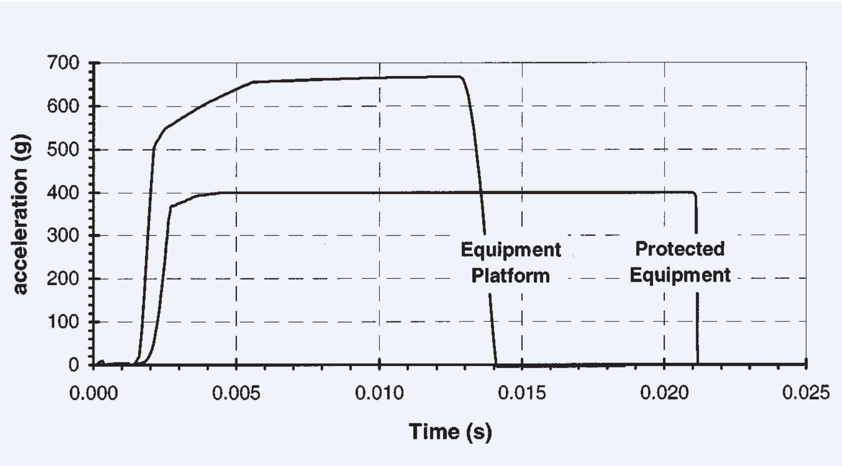


Figure 7. Acceleration profiles of platform and protected equipment

terms of crush stroke and elastic displacement. However, an absorber connected in parallel with a spring-damper element can be used to roughly reposition the payload in its original orientation after the shock load has died down, if elastomer stops are used to restrict the free oscillatory motion.

Experimental investigations of shock-absorbing materials

Static- and dynamic-loading deformation characteristics have been experimentally determined for materials found suitable for the main penetrator-lander impact attenuation device (flared honeycomb skirt) and for a number of payload-equipment energy absorbers (aluminium honeycombs and foams) for both the penetrator and semi-hard landers.

The materials selected for the penetrator lander were HEXCEL aluminium honeycombs 5/32-5052-.0007 (cell size - material grade - wall thickness) for the main skirt and types 3/8-5052-.001, 1/4-5052-.0007, and 3/16-5052-.0007 for equipment protection. The materials selected for equipment protection on the semi-hard lander were HEXCEL aluminium honeycombs 3/8-5052-.0007 (Fig. 8, above) and 1/8-5052-.0007 as well as aluminium foams made by Alcan (Fig. 8, below) and Shinko Wire (Alporas foam).

Static crushing tests were performed on standard test machines and the dynamic crushing tests were carried out using an air-gun facility (Fig. 9). The test conditions and results are summarised in Table 1. The shaded columns indicate the materials selected for application in the prototype devices.

Conceptual design and analysis of shock-alleviation devices

Penetrator-lander

The material tests show that attempts to dynamically crush samples whose heights are considerably greater than their widths lead to undesirable lateral collapsing of the honeycomb stack. An extended attenuation device for load limitation below 400 g (Fig. 6) therefore needs a lateral guiding system for the payload and honeycomb stack.

The proposed shock-alleviation concept foresees installing the equipment to be protected and the honeycomb stack within a tube which offers lateral support (Fig. 10). The guide tube is bolted to the side walls of a solar-array support structure and through the payload platform. The tube is vented to avoid trapped gas being compressed and increasing the reaction loads experienced by the equipment. The venting slots also assist in reducing the overall mass of the device. The ISIM lumped-mass model was used to design the absorber element. A finite-element analysis of the guide-tube structure indicates sufficient safety margins in terms of strength.

Semi-hard lander

The prototype concept has guide rails to

Figure 8. Aluminium honeycombs and foams tested for shock absorption

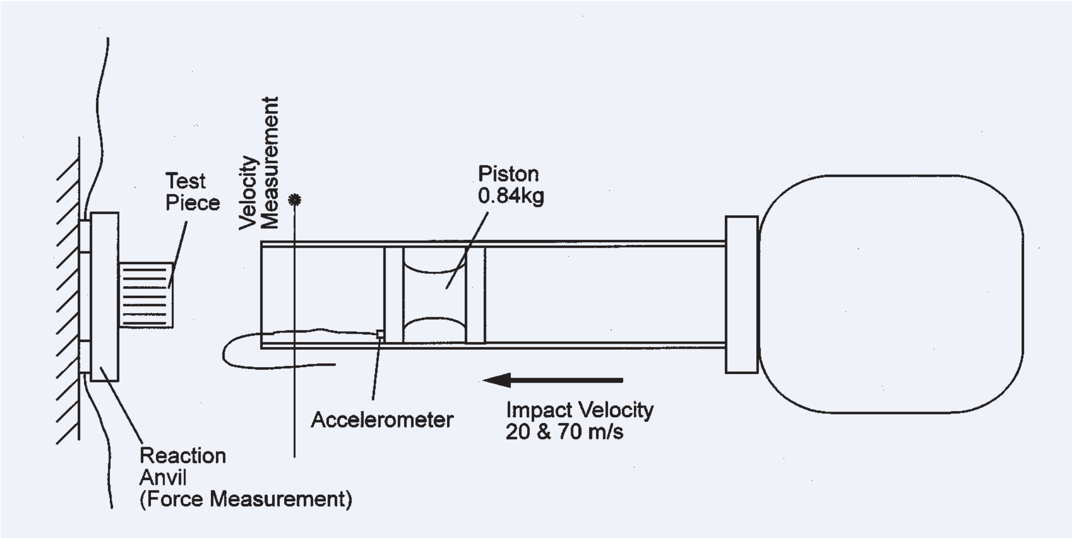


Figure 9. Air-gun facility used for dynamic crushing tests

Table 1. Summary of materials tests

Material	HEXCEL 5/32-5052-.0007	HEXCEL 3/8-5052-.001	HEXCEL 1/4-5052-.0007	HEXCEL 3/16-5052-.0007	HEXCEL 3/8-5052-.0007	HEXCEL 1/8-5052-.0007	Alcan aluminium foam	Shinko Wire / Alporas aluminium foam
Quoted strength [MPa]	0.62	0.32	0.32	0.45	0.17	0.90	0.2	1.0
Mass density [kg/m^3]	41.6	25.6	25.6	32.0	16.0	49.7	77.9	144.9
Static								
Measured strength [MPa]	0.68	0.32	0.38	0.51	0.16	0.94	0.17	0.86
Measured/quoted [%]	+9.6	+0.0	+18.7	+13.3	–5.9	+4.4	–15.0	–14.0
Normalised strength [N/cell]	10.2	28.9	14.2	13.5	15.4	10.4	–	–
Specific energy absorption [kJ/kg]	13.8	9.3	9.8	11.5	10.0	18.9	2.2	5.9
Blocking strain	>0.7	>0.7	>0.7	>0.7	>0.7	>0.7	–	–
Data consistence	good	good	good	good	good	good	good	good
Dynamic								
Impact velocity [m/s]	70	–	70	–	20	20	20	20
Measured strength [MPa]	0.83	–	0.40	–	0.25	1.1	0.19	?
Measured/quoted [%]	+33.8	–	+25.0	–	+47.1	+17.0	+11.8	?
Normalised strength [N/cell]	12.5	–	15.0	–	24.4	12.2	–	?
Specific energy absorption [kJ/kg]	15.1	–	10.5	–	23.6	12.3	2.5	?
Data consistence	good	–	good	–	good	poor	good	poor
General								
Availability	good	good	good	good	good	good	poor	good
Chosen for application	yes	no	yes	no	yes	no	no	no

prevent lateral motion and offers the option of a rough re-positioning and re-alignment of the payload. It was clear from previous analyses that lateral acceleration would not be critical. The main requirements on the concept, known as the Shock Alleviation/Re-Alignment (SA/R) prototype device, are:

1. The device must be able to carry a payload or equipment with dimensions of 100x100x100 mm^3 and a mass of 0.7 kg.
2. The shock loads to be borne by the device are 200 g vertically and 60 g laterally, both applied as 5 ms half sine pulses.
3. In the vertical direction, the 200 g load has to be reduced below 100 g across the whole frequency range. Also laterally, the 100 g limit must not be exceeded.
4. The SA/R device must allow payload re-positioning and re-alignment with 1 mm accuracy in the vertical and lateral directions and with 1deg angular accuracy.

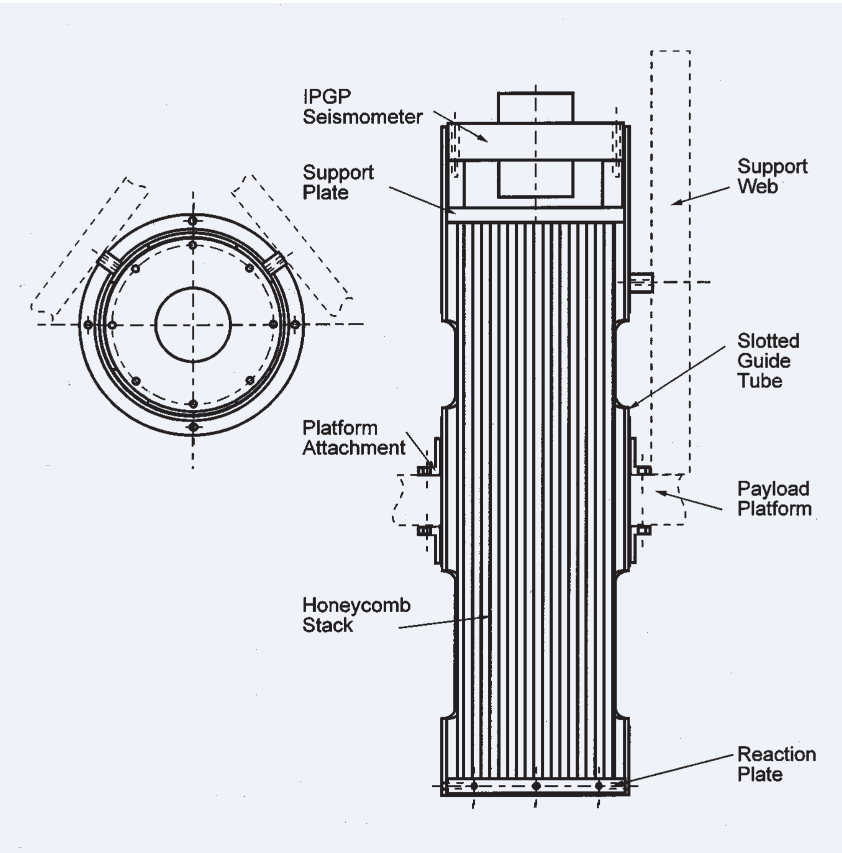


Figure 10. Guide-tube shock alleviation concept

These requirements are reflected in the basic concept for a prototype SA/R device:

1. The payload or equipment is mounted on a support platform with a well-defined interface. The payload plus platform constitute the moving element of the device and their combined mass has to be considered for shock alleviation.

2. The 200 g vertical shock load is reduced to below 100 g by the crushing of an aluminium honeycomb cushion (type HEXCEL 3/8-5052-.0007). Lateral shock loads are carried by a guiding system which has to prevent sticking or canting of the payload platform.

3. Re-alignment of the payload is accomplished with one or more spring elements which take the platform back to its intial position after the shock load has died down. The upward movement of the platform is stopped by elastomer limit stops. The spring elements have to be pre-stressed against the elastomer elements so that the platform comes to rest in a pre-defined position.

Detailed testing and analysis of the main elements (absorber cushion, spring elements, elastomer stops) was conducted in order to complete the SA/R prototype device's design. Performance simulations were carried out with ABAQUS lumped-mass models, including elements for the honeycomb cushion (elastic-plastic with isotropic hardening), springs (non-linear) and elastomer stops (nonlinear spring with linear damper). For the lateral acceleration testing, an inclined adapter was designed. The design drawings of the assembled device are shown in Figure 11.

Testing of prototype devices

Penetrator-lander

The dynamic testing of the penetrator-lander shock-alleviation system was performed with a ballistic air-gun shock-test rig (Fig. 12). A cylindrical aluminium projectile was fired into a

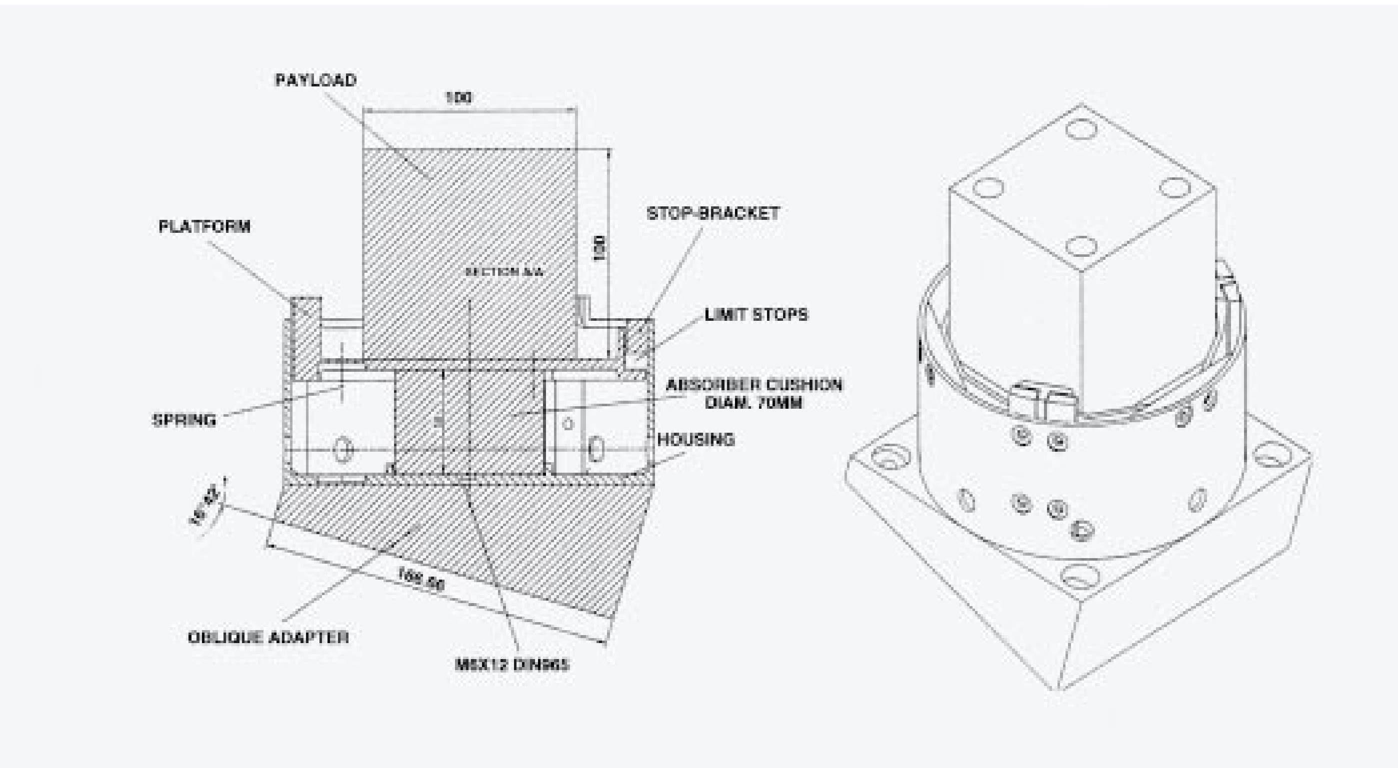


Figure 11. Integrated SA/R prototype device with inclined adaptor

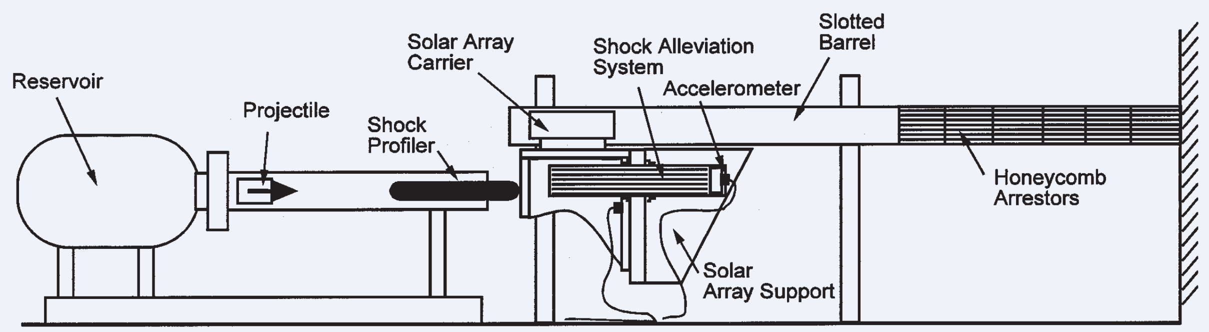


Figure 12. The revised test configuration

polyurethane block (shock profiler) installed on the back of a stationary carrier on which the shock-alleviation device was mounted. During the impact pulse, the kinetic energy of the projectile is transferred via the shock profiler to the carrier, and generates an acceleration profile approximating a half-sine pulse. The carrier and test items are brought to rest using a honeycomb retardation system. An air-gun is used to accelerate the aluminium projectile up to the required impact velocity (typically 80 m/s for the 700 g test). The assembled shock-alleviation device was mounted on the vertical face of the carrier which is attached to a piston located within a slotted guide tube. Additional test items were placed on the baseline mass: three PULNIX CCD cameras, an IPGP seismometer pivot, and a SITe 1024x1024 CCD wafer.

The acceleration measurements verified the functionality of the concept, as the test results summarised in Table 2 confirm. Upon inspecting the degree of deformation of the honeycomb stacks, however, it was found that the test configuration was not performing exactly as predicted. This was found to be because of the reverse ballistic test configuration, where the velocity profile between carrier and baseline mass differs from the actual impact situation on a penetrator-lander. By using a revised lumped-mass model, the crush strokes could be verified analytically.

The models did demonstrate that the deformation characteristics of the honeycomb derived during the initial experimental phase of this study were representative. The predicted baseline mass responses, in terms of amplitude and deformation, correlated very well with those measured during the trial.

Semi-hard lander

The shock tests on the SA/R prototype device were performed in this case on an Avco shock-test machine. The test specimen was mounted on a table, lifted to a pre-specified height and accelerated downwards by air pressure acting on a piston. Various shock-pulse shapes could be realised by choosing appropriate strokes,

Table 2. Summary of inputs and responses

Test No.	Item	Piston Vel.	Carrier Acc.	Duration	Allev. Acc.	Duration	Stroke
WP 3300(1)	PULNiX	49 m/s	270 g	0.016 s	380 g (270g)	0.003 s (0.016 s)	0 mm
WP 3300(2)	PULNiX	81 m/s	700 g	0.012 s	440 g	0.010 s	27 mm
WP 3300(3)	PULNiX	78 m/s	680 g	0.015 s	440 g	0.013 s	26 mm
WP 3300(4)	IPGP	83 m/s	680 g	0.015 s	300 g	0.016 s	70 mm
WP 3300(5)	SITe	79 m/s	620 g	0.015 s	121 g*	-----	180 mm

*calc

air-pressure values, and elastomer impact pads.

The SA/R prototype device was tested in two configurations, namely in a vertical and in an inclined configuration (Fig. 13). Three vertical tests (V1-V3) and two inclined tests (I1, I2) were performed, and the results are summarised in Table 3. The acceleration measurements indicate the proper functioning of the shock-alleviation system, including the 100 g acceleration limit and the rough re-positioning and re-alignment of the payload. However, the crush strokes of the device recorded during the tests were less than half of the analytically predicted values. The kinetic energy measured from the force versus stroke curve during the test was only half that obtained analytically for a half-sine pulse. Simulations using the test acceleration input data correlated well with the experimental results. An additional test with an inclined configuration with 300 g input yielded the kinetic energy specified for the nominal test case.

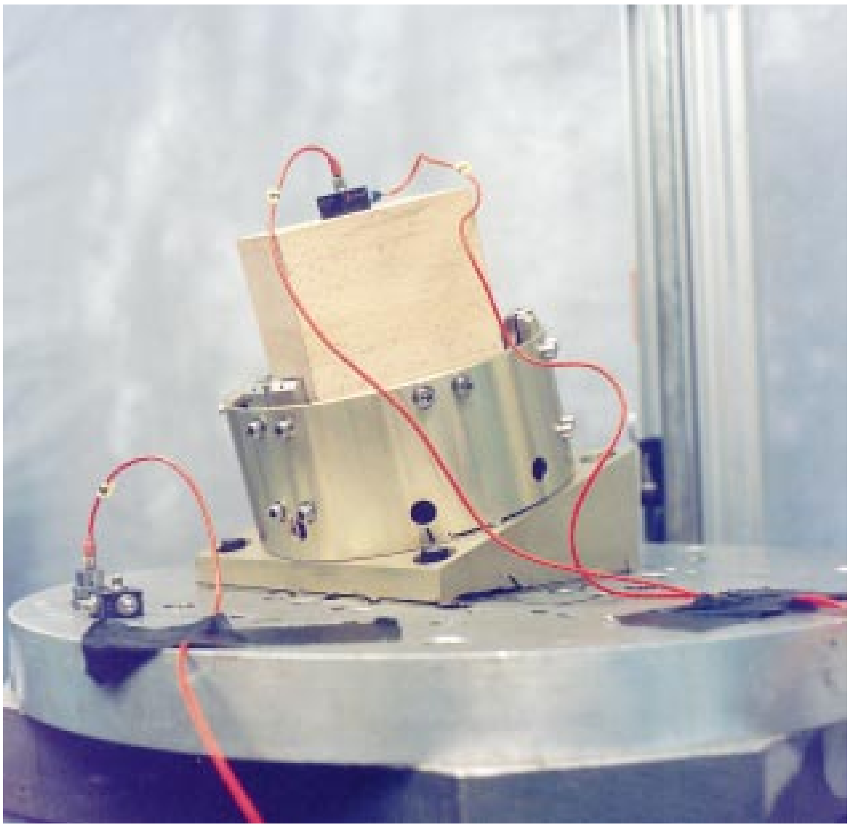


Figure 13. SA/R prototype in test configuration

In the case of the inclined tests, there was a significant dynamic magnification of shock loads, but this was not critical for the 200 g tests. This effect should be further investigated in any future studies/tests.

In general, it was found that simplistic one-dimensional ABAQUS models give reasonably good analytical predictions in the face of significant material data scatter and unknown damping and friction characteristics.

Conclusion

Design specifications for shock-alleviation devices for penetrator-landers and semi-hard landers have been defined on the basis of a review of currently foreseen missions involving lander-type devices. Materials testing and dynamic analyses have helped us to understand the behaviours of shock-absorbing materials such as aluminium foams and honeycombs in such applications. The tests that were subsequently carried out have proved the feasibility of the design concept. The reverse ballistic testing configuration led to smaller crush strokes than predicted for the lander. This could be explained with velocity profiles differing from the actual landing case, and the test results were verified analytically with simplistic lumped-mass models. The predicted baseline mass responses correlated very well with those measured during the trials.

The SA/R prototype device for the semi-hard lander was tested on a standard shock-test machine and its performance successfully demonstrated by experiment for both vertical and inclined configurations, including the requisite rough re-positioning and re-alignment of the payload

Table 3. Summary of test results for the SA/R prototype device

Test No.	V1	V2	V3	I1		I2	
				vertical	lateral	vertical	lateral
Absorber cushion No.	#2	#1	#3	#4		#5	
No. of honeycomb cells	30	30	29	29		29	
max. input acceleration	205.5 g	204 g	205.2 g	185.3 g	55.6 g	291.0 g	87.3 g
max. payload acceleration	68.0 g	84.3 g	71.7 g	75.7 g	92.2 g	90.3 g	146.2 g
max. payload deceleration		–31.4 g	–35.4 g	–27.1 g	–85.7 g	–65.3 g	-140.6 g
crush stroke	9.8 mm	8.6 mm	10.0 mm	7.0 mm		17.2 mm	