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RTG IMPACT RESPONSE TO HARD LANDING DURING MARS ENVIRONMENTAL SURVEY (MESUR) MISSION

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ABSTRACT

The National Aeronautics and Space Administration (NASA) is studying a seven-year robotic mission (MESUR, Mars Environmental Survey) for the seismic, meteorological, and geochemical exploration of the Martian surface by means of a network of ~16 small, inexpensive landers spread from pole to pole. To permit operation at high Martian latitudes, NASA has tentatively decided to power the landers with small RTGs (Radioisotope Thermoelectric Generators). To support the NASA mission study, the Department of Energy's Office of Special Applications commissioned Fairchild to perform specialized RTG design studies. Those studies indicated that the cost and complexity of the mission could be significantly reduced if the RTGs had sufficient impact resistance to survive ground impact of the landers without retrorockets. Fairchild designs of RTGs configured for high impact resistance were reported previously. Since then, the size, configuration, and impact velocity of the landers and the power level and integration mode of the RTGs have changed substantially, and the previous impact analysis has been updated accordingly. The analytical results, reported here, indicate that a lander by itself experiences much higher g-loads than the lander with an integral penetrator; but that minor modifications of the shape of the lander can very substantially reduce the maximum g-load during landing, thus eliminating the need for retrorockets for RTG survival.

INTRODUCTION

NASA has been studying missions to distribute a large number (~16) of small unmanned landers over the surface of the Martian globe, ranging from equatorial to polar regions. These studies have gone under the name of Mars Global Network at NASA's Jet Propulsion Laboratory (JPL) [1] and of Mars Experimental Survey (MESUR) at NASA's Ames Research Center [2]. The most important characteristic of a Mars network mission is that it will send landers to widely dispersed sites on the Martian surface.

When fully deployed, the robotic landers will form a global network to simultaneously collect seismic and meteorological data over a period of seven years. The scientific objectives of the mission will include data sampling relating to the internal structure of the Martian crust, global circulation, geochemistry of the soil, the chemical composition of residual polar caps, and high-resolution surface imaging. Particular emphasis will be placed on hard-to-reach sites (polar deposits, rugged volcano flanks, etc.) that would be difficult or impossible to investigate by any other means.

Since the simultaneous operation of large number of landers over a long period of time is required, the landers must be capable of long life. They must be simple so that a large number can be sent at affordable cost, and yet rugged and robust in order to survive a wide range of landing and environmental conditions.

NASA has baselined the use of Radioisotope Thermoelectric Generators (RTGs) to power the probe, lander, and scientific instruments. Considerations favoring the use of RTGs are their applicability at both low and high Martian latitudes, their ability to operate during and after Martian sandstorms, and their ability to withstand Martian ground impacts at high velocities and g-loads.

High impact resistance of the RTGs can be of critical importance in reducing the complexity and cost of the lander. This is because experience has shown that the other components of the lander can be adequately hardened, so that the RTG's impact tolerance is the controlling determinant of allowable impact velocity. Hard impacts could of course be avoided by using retrorockets to decelerate the lander before impact, as was done for the 1976 Viking landings on Mars. But deceleration systems to achieve soft landing require complex attitude control systems and tend to be quite massive and costly. This was acceptable for the large Viking landers, but would not be for the 16 small landers for the present mission, which must be designed for minimum complexity and cost.

Thus, the greater the impact velocity that the RTG can survive, the lower the complexity, mass, and cost of the system required to decelerate the spacecraft. Therefore, high impact resistance was one of the dominant goals for the RTG designs we presented in an earlier paper [3]. Quasi-static analyses described in that paper indicate that those RTGs could withstand impact loads up to 2000 g, and impact analysis showed that the lander design initially favored by JPL resulted in a peak g-load of 1300 g at the maximum predicted impact velocity of 100 m/s. But that design called for a mechanically coupled penetrator and lander. The presence of the penetrator was beneficial, in that it slowed down the deceleration process and thus reduced the maximum g-load experienced by the lander.

Subsequently, NASA's Ames Research Center proposed a smaller and less costly design concept for the MESUR mission, and was authorized by NASA to conduct a more detailed study based on that concept. The results of that study were reported last year [2], and the study is now continuing at JPL.

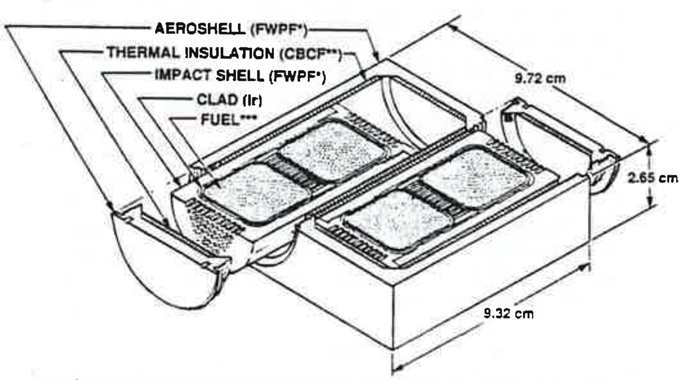
The smaller and lighter lander design proposed by NASA/Ames has a significantly lower impact velocity (30 instead of 100 m/s) but does not have a penetrator to help slow down the lander. The goal of the present paper is to determine the maximum g-load that would be experienced by the lander without penetrator (and without retrorockets or air bags), and to determine how much those g-loads could be reduced by minor changes in the lander design, and to analyze the resultant stresses and survivability of the impact-resistant RTG on such a lander.

RTG DESIGN

The ultimate power requirement for the mission is still uncertain, but the basic RTG design approach would remain the same. The study reported last year [3] presented two illustrative RTG designs: a 9-watt design for direct communication to Earth and a 3-watt design for communication through an orbiting relay. Both designs strove to maximize the use of previously developed technology, including the General Purpose Heat Source (GPHS) [4] used in the Galileo and Ulysses RTGs [5]; the SiGe thermoelectric materials employed in the RTGs for the Voyager, LES 8/9, Galileo and Ulysses missions, and the multicouples developed for DOE's Mod-RTG program [6,7]. Modifications were introduced only where necessary to improve the RTG's impact resistance and to meet other mission requirements.

Fairchild has completed detailed thermal, electrical, and mass analyses of the two RTG designs and a preliminary quasi-static analysis of the their impact resistance. A brief discussion of the 9-watt design follows, the details of which have been presented in the earlier paper [3].

To take advantage of previously developed technology and safety tests, the heat source should be a derivative of the flight-qualified 250-watt General Purpose Heat Source (GPHS) module, depicted in Figure 1.



*Fine-Weave Pierced Fabric, a 90%-dense 3D carbon-carbon composite
**Carbon-Bonded Carbon Fibers, a 10%-dense high-temperature insulator
***62.5-watt $^{238}PuO_2$ pellet

Figure 1. General-Purpose Heat Source Module (250 Watts)

As shown, each GPHS module contains four fuel capsules. Therefore, if we wish to use the standard GPHS fuel capsules the heat source's thermal power can only be varied in steps of 62.5 watts.

For a 9-watt RTG, the thermal power requirement can be satisfied with just three of the four standard fuel capsules shown in Figure 1. The left segment of Figure 2 shows a heat source containing three such capsules, embedded in an impact shell, thermal insulation, and aeroshell of the same graphitic materials and shell thicknesses as the standard GPHS module.

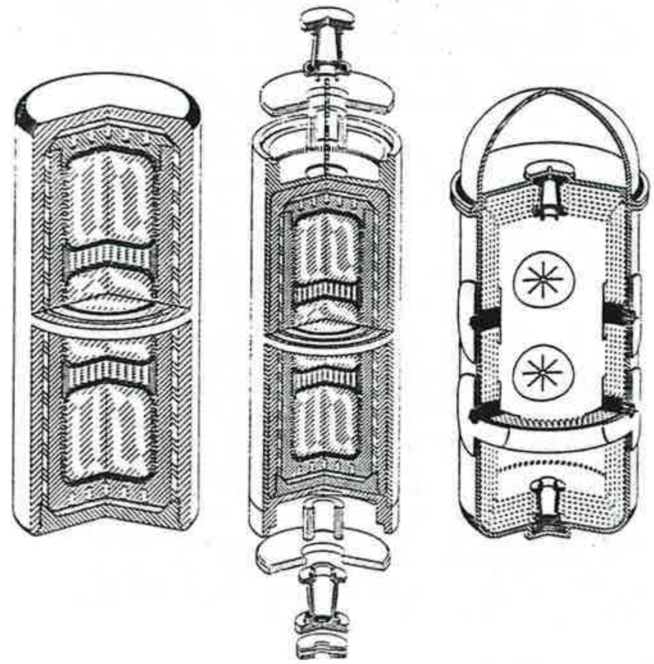


Figure 2. Principal Subsystems of 9-Watt RTG

Similarly, the figure's middle segment shows the heat source with its canister and support structure. The purpose of the canister is to separate the helium generated by alpha decay from the thermoelectric converter surrounding the heat source.

The right segment of Figure 2 shows a sectioned view of the 9-watt converter, without the heat source. As seen, it contains six thermoelectric multicouples similar to those used in the Modular RTG [6,7]. They are arranged in two layers of three multicouples. The figure segment shows that the multicouples' heat collectors cover only a small fraction of the heat source surface. And yet the multifoil insulation is so effective that about two thirds of the generated heat flows through the thermoelectric elements.

Figure 3 depicts the assembled 9-watt RTG, with its dimensions and mass breakdown; and Figure 4 shows its salient operating temperatures and performance characteristics.

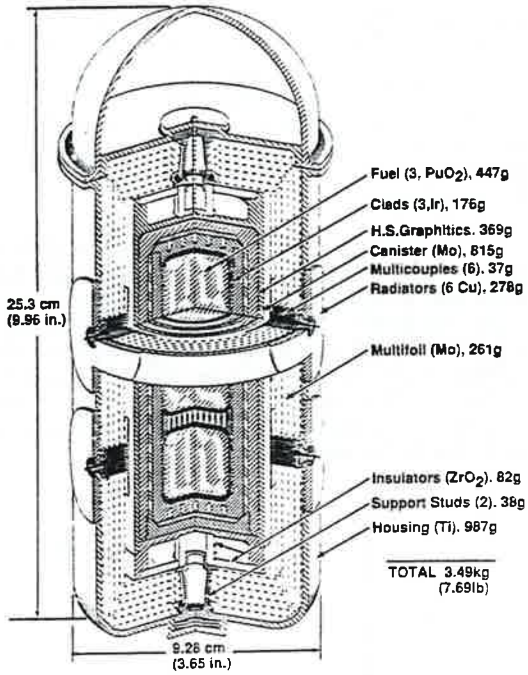


Figure 3. Nine-Watt RTG

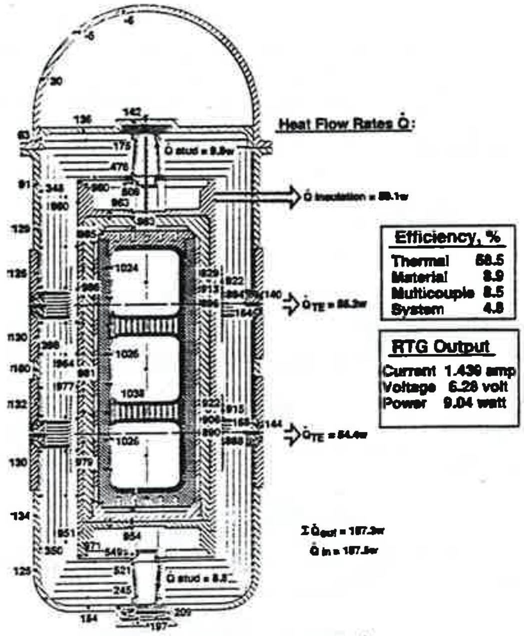
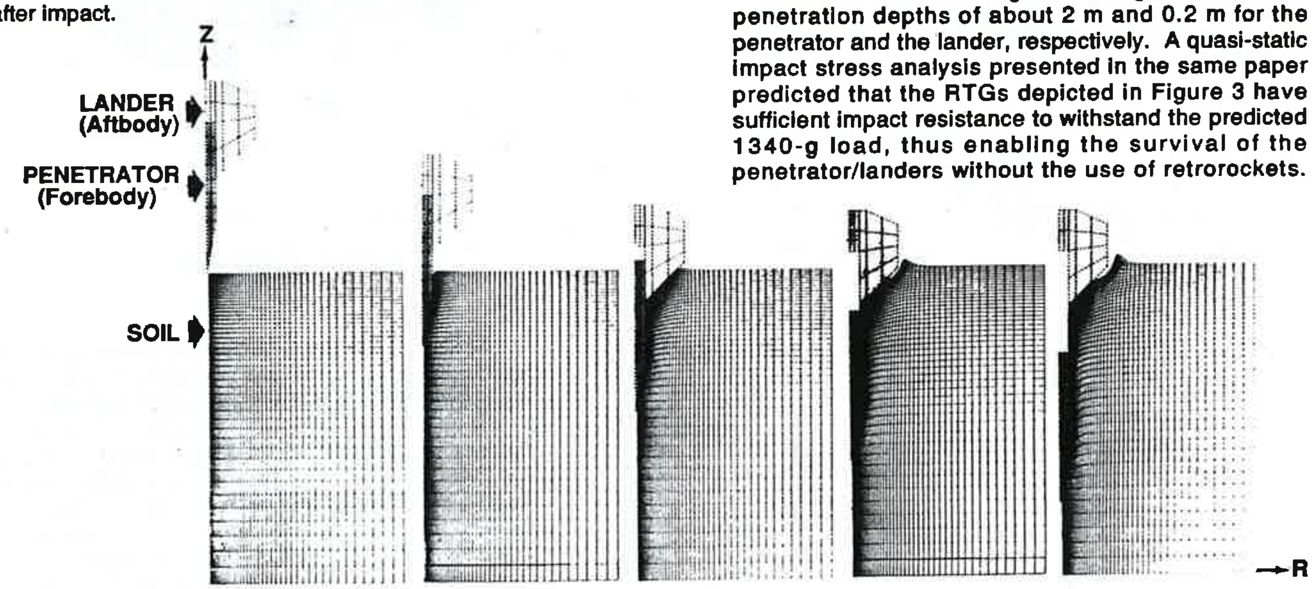


Figure 4. Operating Temperatures (°C) and Heat Flow Rates in 9-Watt RTG

INITIAL LANDER DESIGN

An earlier design concept by JPL [1] assumed a combination penetrator/lander, with the sharp-nosed penetrator acting as a forebody and the blunt-nosed lander acting as the aft-body. As illustrated in Figure 5, the two are together at impact but are free to separate after impact.

Detailed hydrocode calculations [3] were performed by Fairchild personnel to assess the peak g-loads experienced by the penetrator/lander combination after impacting the Martian surface at 100 m/sec, the velocity predicted by JPL if no retrorockets are used. As illustrated in Figure 5, these calculations showed peak deceleration loads of 540 g and 1340 g and maximum penetration depths of about 2 m and 0.2 m for the penetrator and the lander, respectively. A quasi-static impact stress analysis presented in the same paper predicted that the RTGs depicted in Figure 3 have sufficient impact resistance to withstand the predicted 1340-g load, thus enabling the survival of the penetrator/landers without the use of retrorockets.



TIME, msec	0	4	8	12	16
PENETRATION, m	0/0	0.39/0	0.73/0.15	1.01/0.20	1.23/0.20
VELOCITY, m/sec	100/100	92/92	76/24	62/2	52/1
G-LOAD	0/0	432/432	540/1340	310/400	270/0

Figure 5. Deceleration of Penetrator/Lander After Impact (Results of Hydrocode Analysis)

The less costly MESUR mission [2] subsequently proposed by NASA/Ames called for a total of sixteen landers, to be launched in groups of four at two-year intervals. After launch, each group was to separate into four probes. These would then fly independently to their Martian destinations, ranging from equatorial to polar regions. The proposed probes were substantially smaller and lighter than those of the previous JPL design.

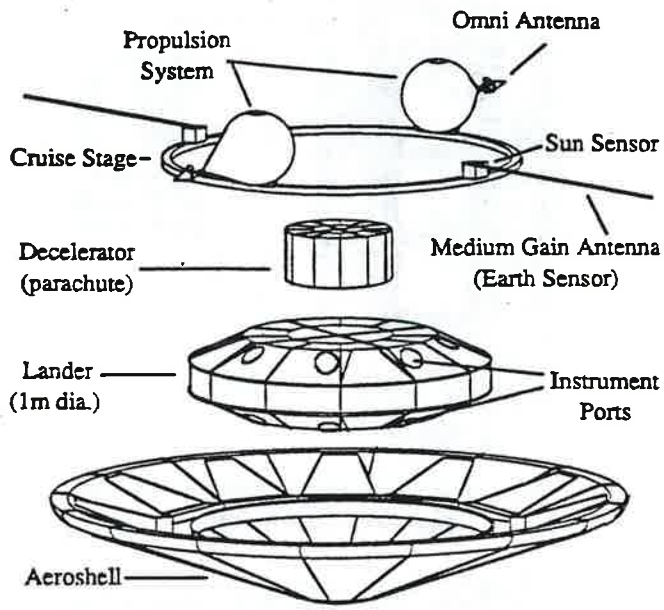


Figure 6. MESUR Probe Components

As shown in Figure 6, the design consists of four principal parts: a cruise vehicle, an aeroshell (for atmospheric entry), a parachute assembly (for pre-impact deceleration), and the lander. The cruise stage, aeroshell and the decelerator are necessary for interplanetary flight, atmospheric entry, descent and landing.

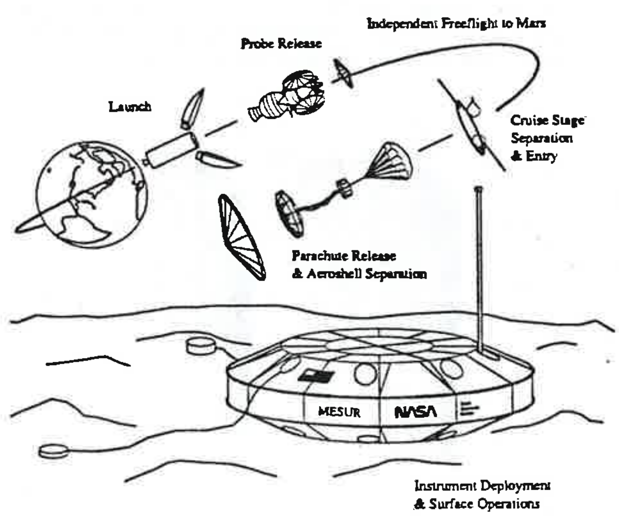


Figure 7. MESUR Mission Summary

The Ames baseline mission scenario, illustrated in Figure 7, assumes that each of the probes flies independently to Mars. Each of these systems is separated from the probe as its portion of flight is completed. The cruise stage is separated before atmospheric entry, after which the aeroshell separates and falls to the Martian surface. The parachute is then deployed to slow down the lander, and separates from the lander and is carried away by a small rocket just before impact.

As depicted in Figure 8, the lander designed by Ames is disk-shaped, about 1 m in diameter and 0.25 m thick, with a total mass of 78.6 kg. The RTG is located inside the lander. The Ames study predicted that the parachute would slow the lander to a maximum vertical velocity of 30 m/s, the horizontal velocity being equal to the local wind velocity (up to 10 m/s). Without retrorockets or air bags, that would be the velocity at which the lander impacts the Martian soil.

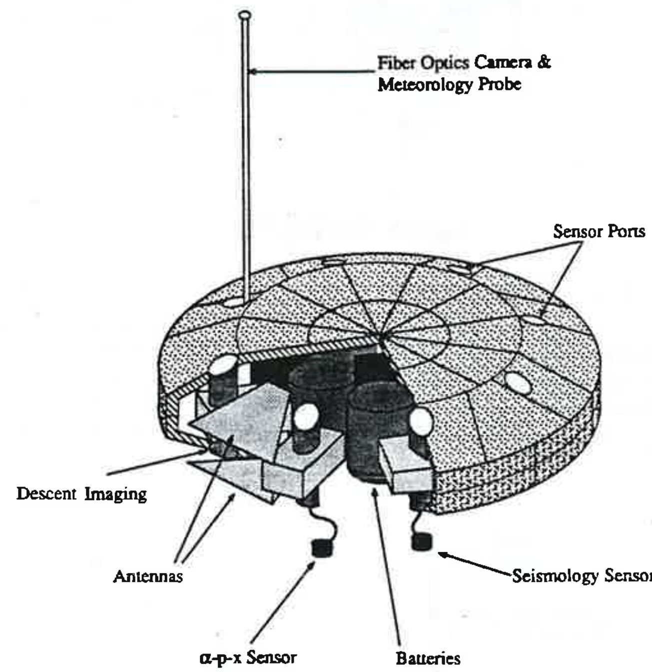


Figure 8. MESUR Lander

To determine the g-loads produced by such an impact, a detailed two-dimensional axisymmetric model of the impact of the lander on representative Martian soil was set up, initially without cross-wind. The analysis employed the continuum-mechanics finite-difference code PISCES [8]. The lander was conservatively modeled as a rigid body impacting Martian soil at 30 m/s. The soil was modeled using a shock equation of state, based on an experimentally determined relationship between shock and particle velocities [9]. The model was based on a bulk sound speed of 172 m/s, a Gruneisen coefficient of 0.25 and a Mohr Coulomb yield model with a yield stress of 350 bars.

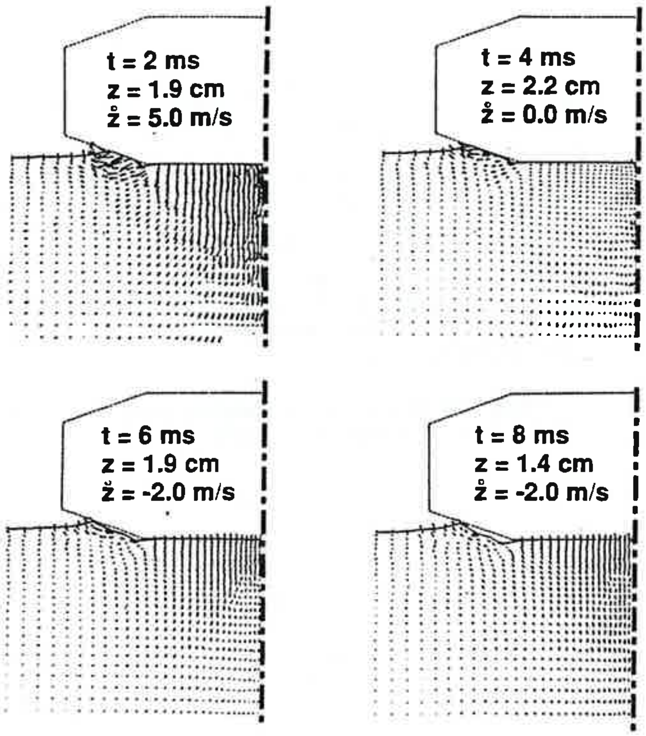


Figure 9. Deceleration of Lander After Impact

The displacement of the soil as the lander penetrates it is shown in Figure 9 at intervals of 2 ms, and the lander's velocity profile is shown in Figure 10. As seen, it penetrates to a depth of 2.3 cm in 4 ms, after which it rebounds. As shown in Figure 10, the lander experiences extremely rapid initial deceleration, resulting in unacceptably high g-loads of ~1.5 x 10^5 in the first 100 μs after impact. Thus, the Ames lander design would experience substantially higher g-loads than the 1340 g peak load calculated for the combination penetrator/lander previously proposed by JPL.

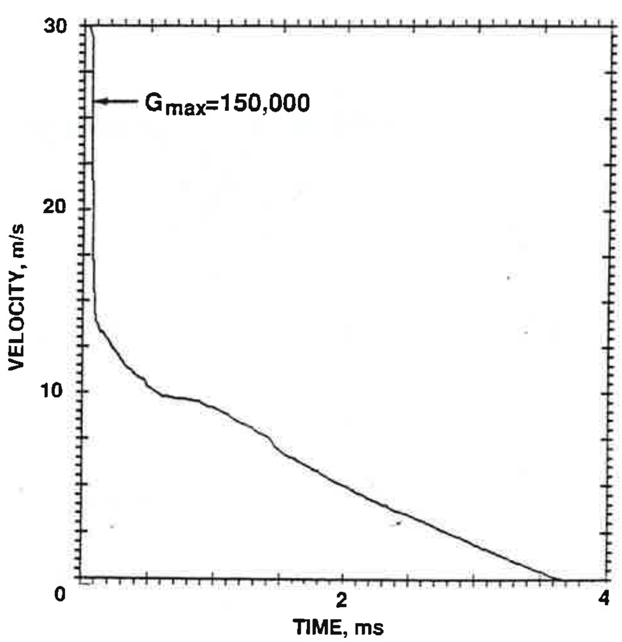


Figure 10. Velocity Profile of Lander After Impact

SHAPE MODIFICATION

The excessive g-load experienced by the lander alone was thought to be the result of the shape of the Ames lander. A large area of the impacting face contacted the Martian soil, causing the lander to decelerate almost instantaneously and resulting in very high g-loads. To attempt to reduce those g-loads, a number of modified but still similar axisymmetric lander shapes were analyzed for the same 1-meter lander diameter and 79-kg mass and the same 30 m/s impact velocity. Several of the modified designs were found to be surprisingly effective in reducing the maximum g-load to survivable levels. The design yielding the most favorable results is depicted in Figure 11.

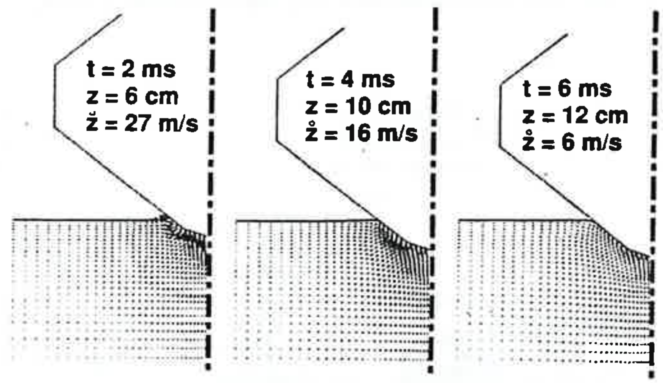


Figure 11. Deceleration of Modified Lander After Impact

Instead of the Martian soil being impacted by a blunt-nosed lander, the large impacting face was split into two coaxial conical faces. The inner one ($0 < r < 7.8$ cm) has a cone angle of 100^o, and the outer one ($7.8 < r < 50$ cm) has a cone angle of 140^o. For that shape, the displacement of soil and the penetration of the lander is shown in Figure 11 at intervals of 2 ms, and the velocity profile of the lander as it penetrates the Martian soil is displayed in Figure 12. As shown, the modified lander penetrates the soil to a depth of 12 cm in 7.5 ms, and experiences a peak g-load of only 500 g, which is far below the 150,000 g of the Ames design shown in Figure 9, and is even below the peak load for JPL's earlier penetrator/lander combination.

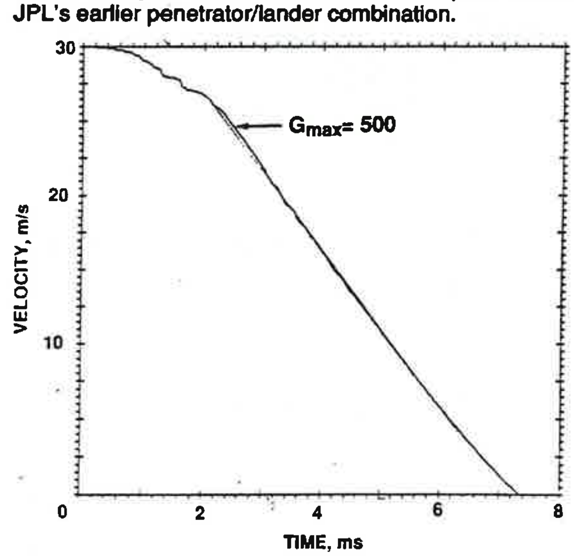


Figure 12. Velocity Profile of Modified Lander

3D CALCULATIONS

The above described analysis assumed vertical descent (i.e., no cross-wind) and a level Martian surface. Neither assumption may be true for a particular landing. To determine the effects of a cross-wind or of a sloping ground, additional analyses were carried out. Since these problems are no longer axisymmetric, a 3-dimensional Lagrangian code had to be employed instead of the 2-dimensional PISCES code used earlier.

The 3-dimensional calculations were performed by means of the AUTODYN-3D code [10] which is a fully integrated three-dimensional engineering analysis program specifically designed for non-linear dynamic problems. The AUTODYN programs are engineering and scientific tools being used for the solution of a wide variety of applications, including the dynamics of impact and penetration. For each problem, a three-dimensional mesh with 30,000 grid points was generated using the Lagrange processor resident in AUTODYN-3D to depict the lander and the soil. The Lagrange mesh moves and distorts with the physical material, which gives an efficient calculation of large deformations and a good definition of free surfaces and material interfaces.

Three specific cases were analyzed using AUTODYN-3D, with the results depicted in Figure 13.

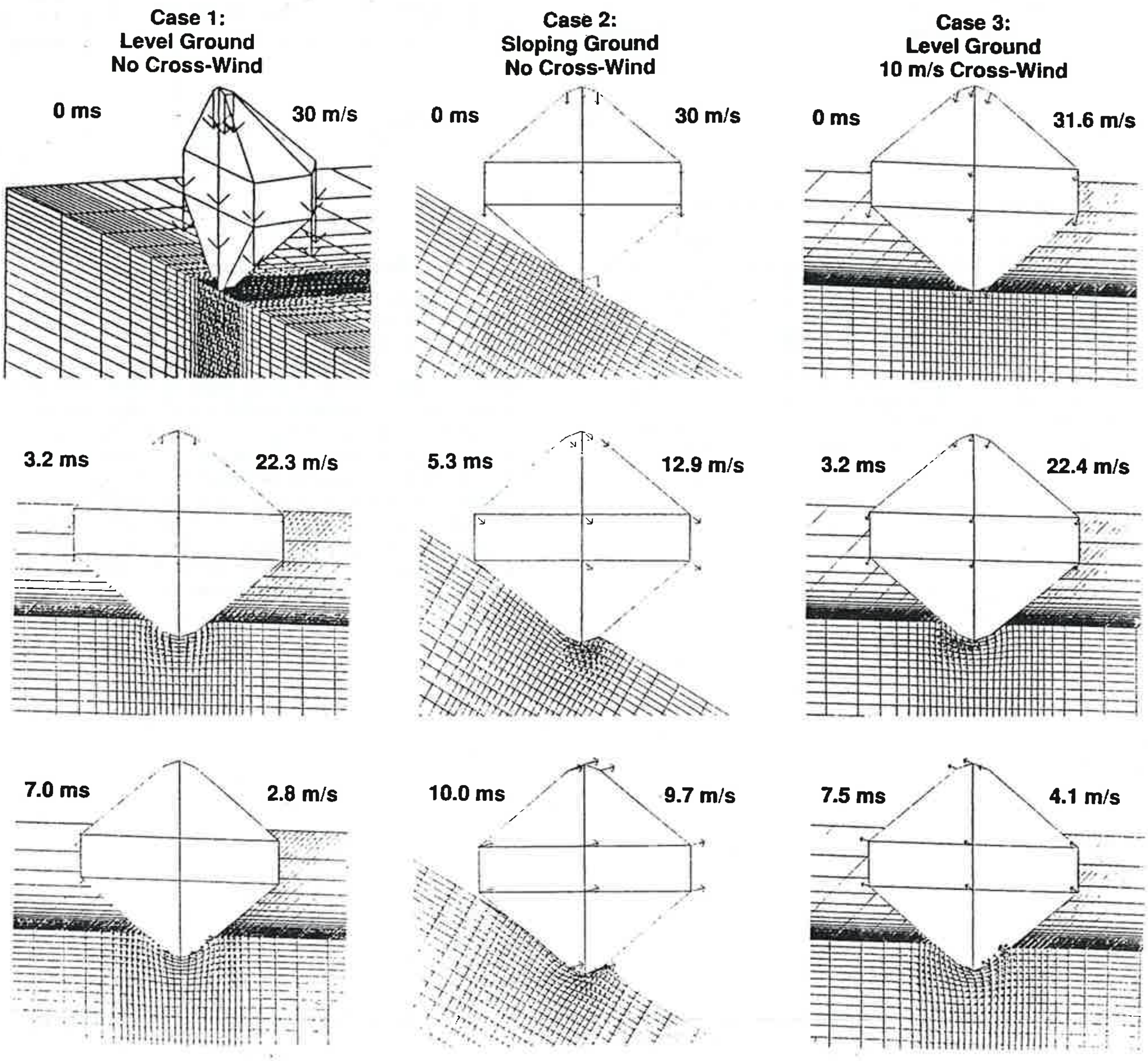


Figure 13. Effect of Sloping Ground and Cross-Wind on Lander Deceleration

Case 1 - A reference case, with the modified lander impacting level Martian soil at 30 m/s without cross-wind. This calculation provides a check against the results described in the previous section using the PISCES-2D code,

Case 2 - The lander impacting the soil which is sloping at 30^{o} to the horizontal, and

Case 3 - The lander having a vertical velocity of 30 m/s and a horizontal component of 10 m/s to account for the cross-wind at the Martian surface.

For each case, Figure 13 shows illustrative snapshots at three different times. Each of the nine pictures shows the time after impact, the residual total (not vertical) velocity of the lander, the lander's penetration into the Martian soil, and the instantaneous velocity vectors of the lander and soil grid points. Note that in the last picture for each case the vectors indicate that the lander's vertical velocity has passed through zero and the lander is rebounding. Also note that in the case of the sloping ground the lander has moved quite a bit to the right (downhill), and in the case of the cross-wind the lander has moved to the left (downwind). The pictures illustrate the power and versatility of the AUTODYN-3D computer code for analyzing complex collisions and deformations on a microsecond time scale.

The deceleration of the lander for the three cases is shown in Figure 14. As can be seen, although the three cases represent very different situations, they yield surprisingly similar velocity profiles and maximum g-loads (~500 g). Thus the modified lander design would be beneficial not only for normal impacts but also in the case of cross-winds and sloping ground. Thus, a relatively minor modification of the lander's shape can substantially reduce the impact loads it experiences.

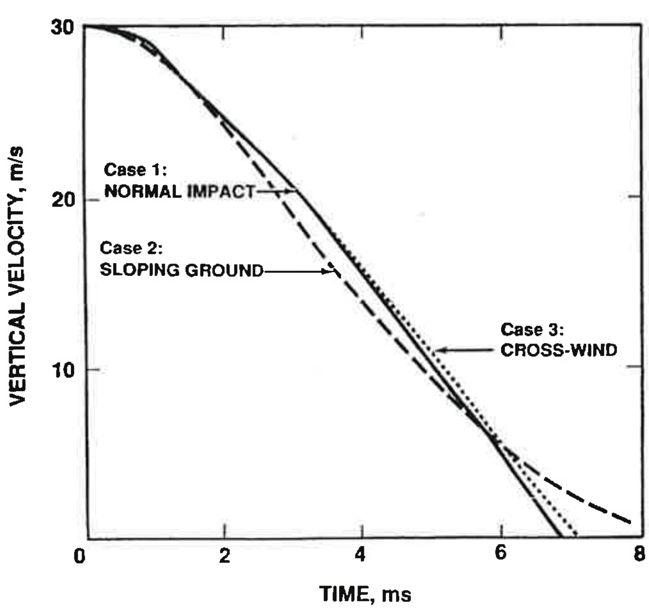


Figure 14. Effect of Impact Orientation on Lander Deceleration

Note that Case 1 is axisymmetric and essentially identical to the problem previously solved by the 2D-PISCES code. Comparison of Figures 12 and 14 show that the AUTODYN-3D code and the 2D-PISCES code yield very similar results for axisymmetric problems. This lends confidence in the validity of using the AUTODYN code for asymmetric as well as axisymmetric problems.

IMPACT RESPONSE OF RTG

As explained in the previous paper [3], the impact tolerance of the RTG is dominated by the response of the cantilevered thermoelectric multicouples to axial and lateral g-loads, specifically by the tensile and bending stresses at the hot and cold ends of their thermoelectric leg assemblies. To determine those stresses, a quasi-static analysis was carried out. Since the orientation of the lander at impact is not predictable, both axial and lateral g-loads had to be analyzed.

The analyses showed that for an axial g-load G, the tensile stress at the leg assembly's cold face is given by $\sigma_{T,C}$ = 0.078 G psi and at its hot face is given by $\sigma_{T,H}$ = 0.022 G psi; and that for a lateral g-load G, the maximum bending stress σ_B at the assembly's cold end is σ_B = 0.343 G psi. Thus, the cold-end bending stress is dominant.

SUMMARY AND CONCLUSIONS

- The MESUR landers proposed by ARC are slowed to 30 m/s by means of parachutes.
- The addition of retrorockets to control the lander's impact orientation and to further reduce its impact velocity would significantly increase its cost and complexity.
- The need for retrorockets can be eliminated if the lander can survive an impact at 30 m/s on the Martian surface.
- The impact resistance of the lander is limited by that of the RTG.
- The impact resistance of the previously proposed hardened RTG design is limited by its most fragile members, the cantilevered multicouples.
- Quasi-static stress analyses of that multicouple showed that the dominant stress occurs at the cold ends of its thermoelectric leg assemblies, due to bending moments induced by lateral g-loads.
- Hydrocode analysis showed that the ARC lander impacting Mars at 30 m/s would result in a peak deceleration rate of 150,000 g, which is not survivable.
- Additional analyses showed that relatively minor modifications of the lander's shape can reduce its peak deceleration rate to just 500 g, for both level and sloping Martian ground, with and without cross-winds.

- For the proposed modified lander shape, the peak deceleration rate of 500 g results in a maximum stress of only 172 psi, which is well within the capability of the thermoelectric legs and the glass bonds.
- Thus, the proposed impact-resistant RTG design and modified lander shape would enable impact survival without retrorockets.
- This could substantially reduce the mission's cost and complexity.

Acknowledgment

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