# The *Surveyor* Shock Absorber*

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*The landing shock absorbers used on the Surveyor spacecraft are described. A hydraulic cylinder and piston arrangement was found to be capable of providing both the required damping and spring action. A digital computer program, simulating the landing process, was used to assess performance and spacecraft landing stability. The shock absorbers performed very satisfactorily throughout the Surveyor program.*

## I. Introduction

The landing gear of the *Surveyor* spacecraft (Fig. 1) consists of three inverted tripod-type landing legs with crushable aluminum honeycomb footpads and three crush blocks (cylindrical pieces of aluminum honeycomb material) mounted on the underside of the spaceframe.

The upper of the three tubular leg members contains a shock absorber spring assembly. The two lower leg members, which are rigid and cross-braced to each other, are hinged to the spacecraft frame (see Fig. 1); at touchdown, they rotate upward, thereby compressing the shock absorber column.

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The function of the shock absorbers was to cushion the spacecraft landing impact and to dissipate the residual kinetic energy of the spacecraft at the time of first ground contact. In addition, parallel springs were required to reextend the legs after impact in order to obtain a defined position of the frame relative to the lunar surface. This was necessary in order to perform the planned lunar surface experiments properly.

While the footpads and the crush blocks were also capable of energy dissipation, this was not intended to be their principal function. The footpads (the lower parts of which consist of aluminum honeycomb with a crushing strength of 10 psi) were designed with the objective of protecting the shock absorber columns from excessive lateral loads during impact. The body blocks, with a crushing strength of 40 psi, were incorporated to secure a ground clearance of at least 4 in. between the frame

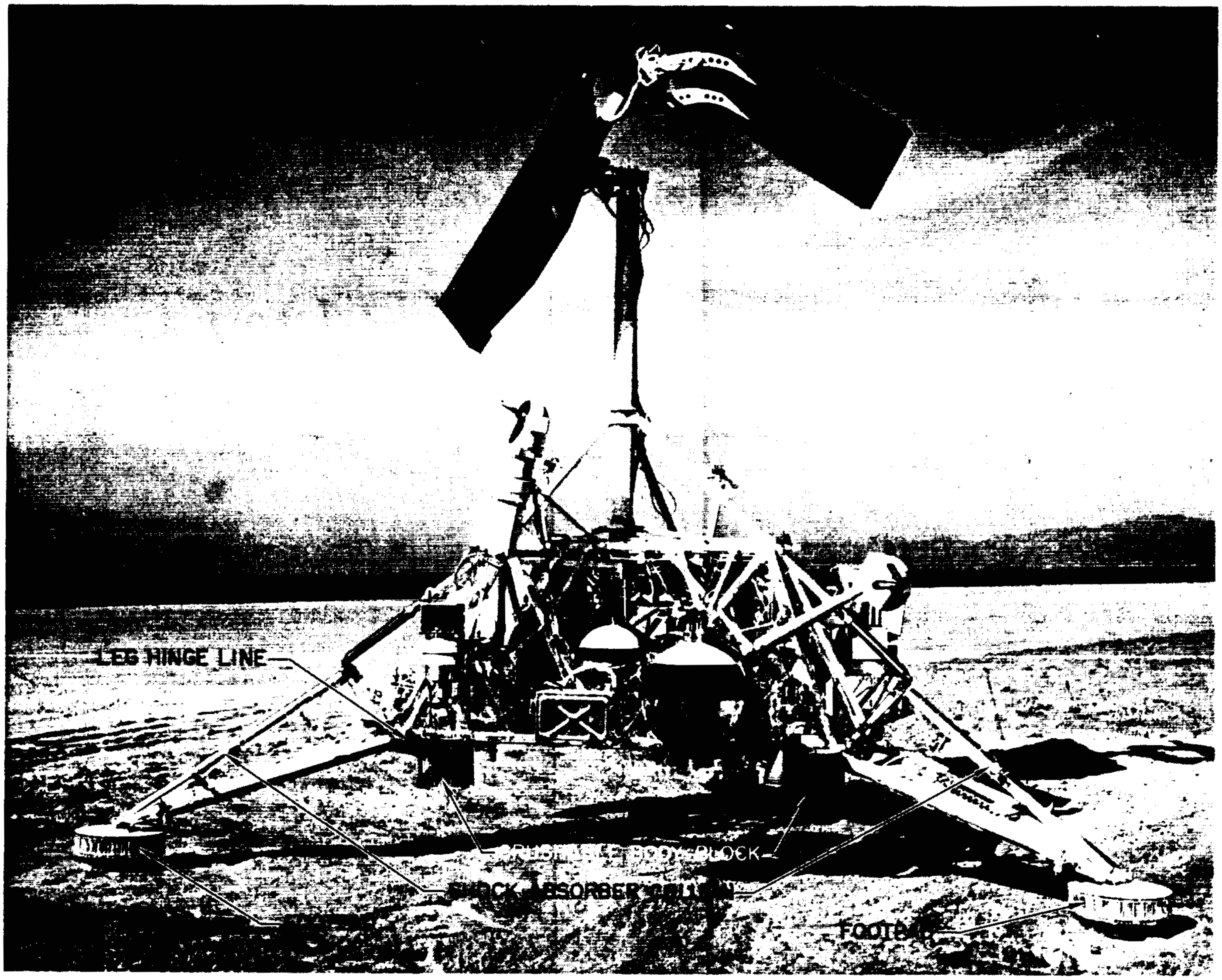



**Fig. 1.** ***Surveyor* spacecraft model in landed configuration**

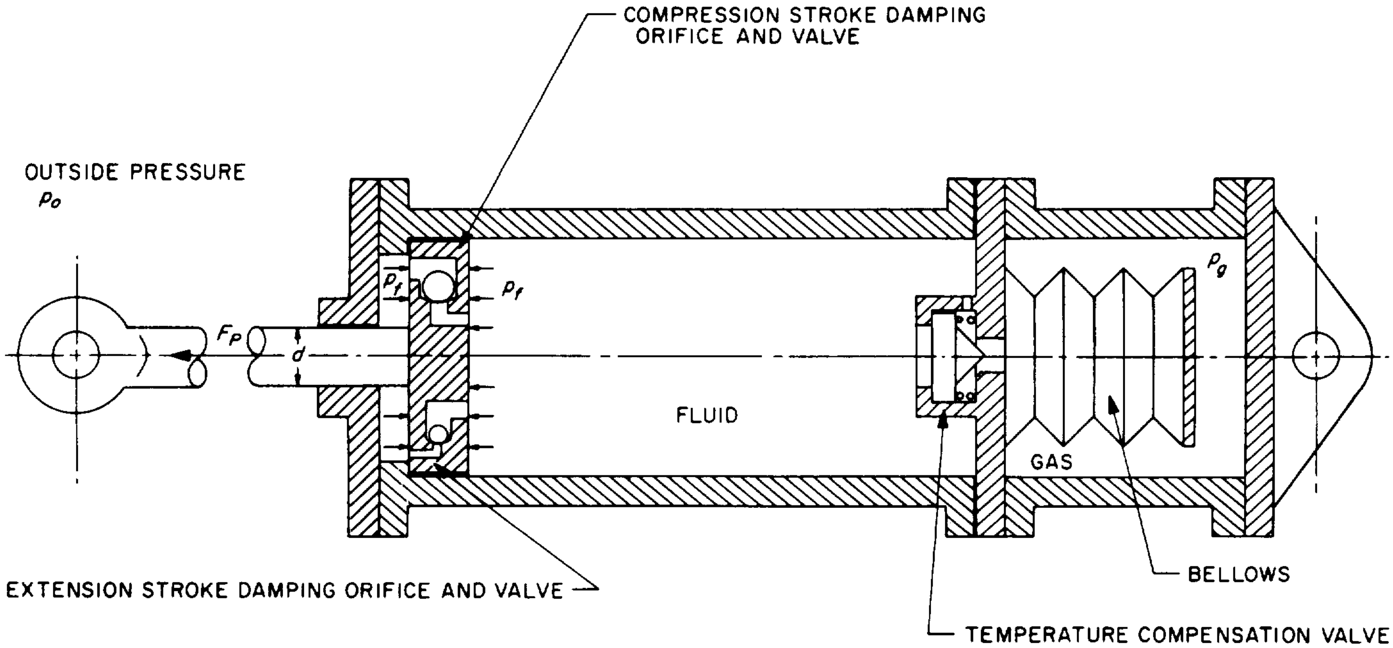
and a planar landing surface, throughout the touchdown phase.

Hence, the shock absorbers had to have the capability of dissipating essentially the entire landing energy. As we now know, this indeed was required of them and was accomplished in all five successful *Surveyor* landings, since practically no footpad or body block crushing took place in any of the landings because of the relative softness of the upper lunar surface layer.

## II. Working Principle

While there was no difficulty in satisfying the functional requirement of a combined spring and damping action with a variety of conventional concepts, the additional requirement of highest possible weight economy could not be met with any type of metallic spring. For the damping action, the dashpot principle, i.e., the forcing of a damping fluid through an orifice, seemed acceptable, and after it was found that the required cylinder and piston arrangement could be utilized to provide the desired spring action at the same time, this concept was adopted.

The working principle is explained in Fig. 2. It is based on the fact that no fluid is absolutely incompressible. Consequently, when a perforated piston (shown schematically in Fig. 2) is pushed into a cylinder entirely filled with fluid and the fluid volume is increasingly




IN EXTENDED POSITION { FLUID PRESSURE = $p_f$ = GAS PRESSURE = $p_g$; SPRING FORCE (PRELOAD) $F_P = (p_f - p_o)\frac{d^2}{4}\pi$ }

IN STROKED POSITION, THE TEMPERATURE COMPENSATION VALVE IS CLOSED AND THE SPRING FORCE IS INCREASED, BECAUSE OF COMPRESSION OF THE FLUID (ENTERING OF PISTON ROD). A DAMPING RESISTANCE IS ALSO ENCOUNTERED, DEPENDING ON THE FLUID AND ORIFICE CHARACTERISTICS AND LINEARLY PROPORTIONAL TO THE SQUARE OF THE STROKING VELOCITY.

**Fig. 2. Working principle of the *Surveyor* shock absorber spring assembly**

reduced by the entering piston rod, the fluid is compressed, resulting in a steep increase in pressure. A restoring force equal to the pressure difference between fluid pressure and outside pressure times the cross section area of the piston rod results.

By pressurizing the fluid above the outside pressure, with the piston in the extended position, a preload can be obtained on the same principle. Since a preload was required to support the weight of the *Surveyor* spacecraft after landing, a provision for fluid pressurization was made by connecting the fluid chamber to metal bellows (Fig. 2) surrounded by a sealed gas chamber. Pressurizing the gas automatically pressurized the fluid to the same level, because of the elasticity of the bellows. However, upon actuation of the piston, the connection to the bellows had to be closed, else the volume reduced by the entering piston rod would have been made up by an extension of the bellows. For this purpose, the spring-loaded temperature compensation valve was incorporated, closing the fluid chamber upon a rapid pressure increase. For a slow pressure rise, however, this valve stayed open, thus allowing the fluid to expand and contract with changing temperature without significantly affecting its pressure and, consequently, the preload.

## III. First Design

Before implementation of the working principle into a design, the specification of such parameters as maximum load, piston travel, and spring and damping characteristics was necessary. It appeared desirable to design a maximum-efficiency shock absorber that would dissipate a certain amount of energy within a certain stroke with the lowest axial peak load, ideally requiring a constant force-vs-stroke characteristic. Since the damping force in an orifice damper varies proportionally with the square of the stroking velocity, the desired characteristic required a variable damping coefficient (i.e., a stroke-dependent variable orifice).

While, theoretically, the loading could have been held to any desired level by allowance of the corresponding stroke length, the latter was limited by considerations of stability and ground clearance during the landing process to a maximum of 4.5 in. Thus, the constant force in the force-vs-stroke characteristic was determined by the condition that no "bottoming" of the shock absorber was to be encountered for the highest specified landing velocities (20 ft/s vertical and 7 ft/s horizontal).

Many factors were considered in determining how this constant force was to be distributed between the spring force and the damping force and whether or not it was desirable, or even possible, to design for the constant-force characteristic. One consideration unfavorable to the latter was that of the fluid chamber design for pressure. At the beginning of the stroke, the opposing force is almost entirely due to the damping effect – i.e., to the difference of pressures acting on the piston face from the left to the right of the piston. At the end of the stroke, however, the force is a pure spring force, dependent upon the absolute fluid pressure (assuming an outside pressure of zero), acting only on the piston rod cross section. To equalize these forces would have required a considerably higher fluid pressure at the end of the stroke than at the start.

Compromising between these conflicting requirements led to an optimized damping profile (a change of damping coefficient vs stroke) to be implemented by a cylinder-fixed metering pin protruding through the damping orifice and thereby changing its size as the piston moved in.

This compression-stroke damping was found to be totally inadequate for the extension stroke; it would have resulted in a high springback of the spacecraft after the initial landing. Consequently, a separate orifice had to be provided for the extension stroke, and two valves (schematically indicated in Fig. 2) were added, to appropriately open or close the two damping orifices.

The extension damping was designed to provide critical damping for the leg extension stroke. Because the characteristic of the fluid spring was not linear, this could be only approximated for one landing condition with one initial velocity. The selected conditions were for a landing on a level surface with the three legs touching simultaneously and with the nominal vertical spacecraft landing velocity of 12.6 ft/s. In this case, after impact and deflection of the legs, the spacecraft was to rise to its prelanding configuration without overshooting.

A titanium alloy containing 13% vanadium, 11% chromium, and 3% aluminum was chosen for the main body, including the fluid cylinder, because of its high strength/weight ratio. Properly heat-treated tensile coupons showed an ultimate tensile strength of 194,000 to 207,000 psi. For the damping fluid, a silicone compound (Dow Corning F-4029) was selected for its high compressibility and its ability to perform without excessive change in viscosity within the specified temperature range from 0 to 120°F.

A lock-finger arrangement was implemented to prevent spacecraft sagging as a result of possible fluid or gas leakage after landing. Two spring-loaded lock-fingers were mounted on the upper stationary part of the assembly and engaged in a collar on the lower telescoping part. These were shaped so that they would break loose if an axial load of the order of the spring preload were applied. Hence, the intended shock absorber operation was not constrained. After reextension of the legs, the lock-fingers reengaged and would not break loose under the loading imposed by the spacecraft weight.

A redundant locking system was provided by pyrotechnically operated pin drivers. Also located on the stationary part of the shock absorber column, this locking device had the capability of being commanded from the earth to drive a pin into a strip of soft aluminum attached to the telescoping part of the assembly.

Unit dimensions are 2 in. outside diameter and 37.53 in. between connection points in the extended position; the weight is approximately 3.9 lb.

## IV. Second Design

During manufacturing and checkout of prototype units, several problem areas became apparent. The selected titanium alloy proved to be hard to machine and particularly difficult to weld. Since the material is brittle and notch-sensitive, each unit became a potential hazard when pressurized to the required room temperature pressure of 1700 psi. It was necessary to impose special shipping and handling procedures to protect the assemblies from even slight scratches or bumps, as well as to protect personnel. Another problem arose in the manufacture of the metering pin. Even though the metering pins were machined to extremely close tolerances, a checkout of assembled units showed a considerable scatter in the damping around the design profile, which specified a damping coefficient that increased considerably more strongly than linearly with increasing stroke.

A reevaluation led to a second design which conformed to the same principle and basic configuration but which deviated significantly from the first in the two areas described below.

First, the material of the basic structure was changed to a titanium alloy with 4% vanadium and 6% aluminum. Although weaker in tensile strength by approximately 20% compared with the original alloy (13% V, 11% Cr, 3% Al), the latter alloy is far less brittle and less notch sensitive and is easier to machine and to weld. The metering pin was eliminated, and an optimum constant orifice size was determined. Although this resulted in a less desirable force-vs-stroke characteristic, the peak force could be kept below the maximum design load of 10,000 lb. It was found that the damping coefficient, even for a constant orifice, is not constant; rather, it increases approximately linearly with the stroke when a constant compression force is applied. This effect results from the increase in fluid pressure with stroke, and it is, in this application, very desirable because it retains, in part, the advantages of a varying damping profile, which had originally led to the metering-pin concept. A further compensation of the force falloff was accomplished by increasing the spring rate.

Second, the lock-finger arrangement was eliminated. Since its break-loose threshold had proved to be difficult to control, it was decided that the backup locking device (the pyrotechnic pin-drivers) would be sufficient. Unit weight of the second design was approximately 4.4 lb.

This second shock absorber design was used with *Surveyors III* through *VII*; *Surveyors I* and *II* utilized the first design. *Surveyor I* performed a successful landing, and *Surveyor II* suffered a propulsion system failure during the midcourse correction maneuver. Of the remaining *Surveyors*, all but *Surveyor IV* landed successfully. Telecommunication with *Surveyor IV* was lost 2.5 min before predicted touchdown.

## V. Analytical Representation

During the conceptual study and design phases of the shock absorber, the most helpful tool for evaluating performance and assessing landing stability and ground clearance was a digital computer program that mathematically simulates the landing process. In this program, the spacecraft structure above the landing gear connection points is represented as a rigid body with adjustable mass and inertia properties. The landing gear, however, is geometrically and dynamically modeled in detail. For any desired initial landing velocities, spacecraft tilt, and ground slope of a rigid planar surface, analytical landings could be performed by means of this program to indicate spacecraft motion, acceleration, landing gear deflections and loadings, and other performance parameters throughout the landing process. In the program, the shock absorber assembly is represented by the following equation:

$$F_S = \frac{\dot{\ell}}{|\dot{\ell}|}\dot{\ell}^2 R_C S_D + K_D S_K (\ell - \ell_0) - F_P$$
$$+ 0.05\frac{\dot{\ell}}{|\dot{\ell}|}[|K_D S_K (\ell - \ell_0) - F_P|]$$

where

$F_S$ = axial shock absorber column force

$\ell_0$ = length of column in extended position

$\ell$ = length of column

$\dot{\ell}$ = change of column length with time

$R_C$ = damping coefficient

$S_D$ = damping coefficient versus stroke profile

$K_D$ = spring rate at zero stroke

$S_K$ = spring rate vs stroke profile

$F_P$ = spring preload

The first term represents the damping force proportional to the square of the velocity; because of the fractioned factor, its sign automatically reverses with each change in velocity direction, which is also used to select the proper damping coefficient and profile for compression and extension, respectively. The second term represents the increase in spring force with stroke; together with the constant preload, represented by the third term, the entire spring force of the fluid spring is expressed. The last term, in magnitude equal to 5% of the spring force, represents an estimated friction force, again reversed in sign as appropriate by the fractioned velocity factor.

In the step-by-step integration, the first delta stroke ($\Delta\ell$) after ground contact is determined by assuming that no forces are acting on the spacecraft – i.e., that the spacecraft is continuing in its path as though the ground had not been encountered, for a preselected time increment $\Delta t$. For the next step, $\Delta l$ and $\Delta t$ are used to define the stroking velocity, while, from the spring and damping profile, the values corresponding to the incremental stroke $\Delta l$ are selected. From this, the shock absorber force is determined and regarded as acting on the spacecraft throughout the next $\Delta t$. As dictated by the spacecraft's equations of motion, this results in a new incremental stroke $\Delta l$, which is used again, as above, for the next $\Delta t$, and so on.

The quality of this analytical shock absorber force representation could be checked directly by comparison with telemetry data from the *Surveyor* landings, as discussed in the performance section of this report (Fig. 3).

## VI. Testing

A very extensive test program was carried out on both type-approval and flight-acceptance levels. The first category included burst tests, vibration tests, leak tests, functional tests, and verification tests for the damping and spring characteristics at room temperature and at the specified temperature extremes. Also conducted were dynamic loading tests, including impact tests, performed in a drop test fixture and increased to the point of unit destruction. Finally, several units were tested in full-size vehicle drop tests with maximum design conditions in respect to landing velocities, vehicle tilt, and ground slope.

The flight-acceptance test series included functional tests, vibration tests, leak tests, preload tests at various temperatures, and verification of spring and damping characteristics at room temperature.

In addition, preload tests were performed on every flight unit before shipment to the launch site and again immediately before installation on the spacecraft. In these tests, each unit was slowly stroked to ¼ in.; the force necessary to initiate and maintain movement was measured. Then, the load was slowly decreased and the unit allowed to extend; again, the force necessary to maintain movement was measured. By this procedure, a check of the preload as well as of the internal friction of the unit was made. For the first design type, this test was conducted with disengaged lock-fingers. If preload and friction were found within acceptable limits, the unit was accepted as fully charged and operational.

## VII. Temperature Control

Although the shock absorbers were required to survive temperature extremes of −300 and +300°F, the temperature range within which they were to be operational

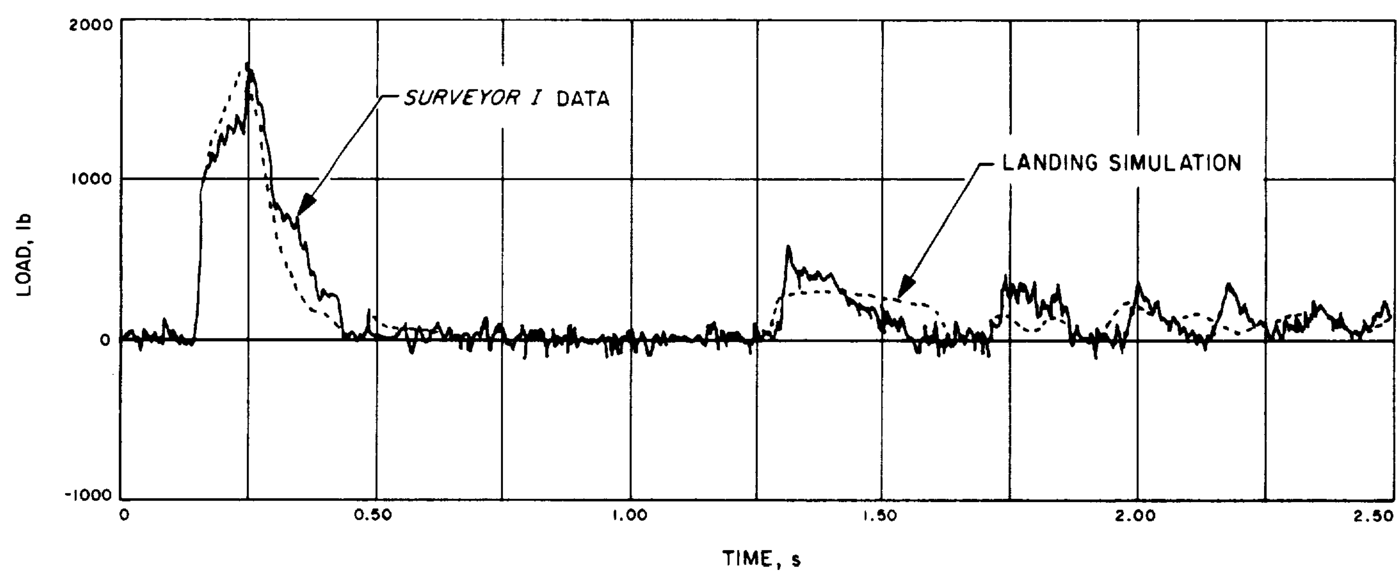



**Fig. 3. History of axial loading of the leg 2 shock absorber column during the lunar landing of *Surveyor I*. (The dashed line represents the same data derived from an analytical landing simulation under identical landing conditions.)**

could be narrowed to between 0 and 120°F. This was achieved by passive temperature control, from application of thermal paint patterns and aluminized Teflon strips.

## VIII. Performance

Each shock absorber unit was equipped with a temperature-compensated strain-gage bridge consisting of four gages attached to the gas-filled cylinder. These were arranged to measure only axial loads. The strain gages, as a part of the engineering instrumentation, were intended to enable assessment of the spacecraft performance during touchdown. The output of the three bridges was transmitted in the form of frequency-modulated, continuous analog data. Within limits, these data could also be used to assess the dynamic behavior of the surface material at the landing site, allowing estimates of lunar surface mechanical properties. Figure 3 shows one of the *Surveyor I* landing shock absorber force histories, together with an analytical simulation. It shows that the compression stroke, building up to a peak force of approximately 1600 lb, lasted about 0.1 s, followed by a 0.2-s extension, at which time the axial force returned to zero, indicating spacecraft rebound. At 1.1 to 1.2 s after first contact, footpad reimpact was registered; this was followed by a ringout oscillation, after which (beyond the time covered in Fig. 2) the force settled at approximately 120 lb, because of the spacecraft's weight. While, in general, a very satisfactory performance of the shock absorber units was found, the rebound was more pronounced than had been expected for a landing with a slightly lower-than-nominal vertical landing velocity. *Surveyor I* landed with 11.6 ft/s vertical velocity (nominal was 12.6 ft/s) on a surface that was within 2 deg of level.

Records very similar to Fig. 3 were obtained from all shock absorbers in each of the successful *Surveyor* landings. Spacecraft rebounding was experienced in all *Surveyor* landings; it was slightly higher with the second design type of shock absorber units because of the increased spring rate of the fluid spring. Although this constituted a deviation from the design specification, the spring-back was not detrimental to the landing or to other performances of the spacecraft. It was even found to be advantageous, since, in some cases, it exposed the first footpad imprints to the spacecraft camera, facilitating scientific soil studies.

The leg locking devices appeared to have worked satisfactorily on *Surveyor I*. In the later missions, however, two instances were observed in which a leg did deflect after the command to actuate the lock-pin drivers had been sent. In both cases, this occurred at the beginning of lunar night and did not affect lunar surface operations.

## Acknowledgment

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Conceptual development and design specification were accomplished by R. E. Deitrick and R. H. Jones of Hughes Aircraft Company, El Segundo, California.

Manufacturing and testing were performed by O. W. Scheflow, T. Scarff, and W. Fruehauf of the National Water Lift Company, a Division of Pneumo Dynamics Corporation, Kalamazoo, Michigan, under subcontract to the Hughes Aircraft Company, and were monitored by R. E. Deitrick and A. L. Peterson of Hughes.

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