Surveyor Spacecraft Vernier Propulsion System Survival in Lunar Environment

GILBERT F. PASLEY*
Hughes Aircraft Company, El Segundo, Calif.

The primary purpose of the soft-landing Surveyor spacecraft was to transmit to earth basic data relative to the moon's environment and characteristics. Although no plans had been made for postlanding operation of the vernier propulsion system (VPS), the VPS was found to have some useful life on the lunar surface and hence the capability to extend the range of scientific data obtainable. During the lunar day, the combined effects of extreme temperature and propellant exposure caused fluid loss through the soft seals and valve seats. The combined effects of high temperature and low pressure dissipated the leakage rapidly, and there was no observable effect on thermal control surfaces, optical surfaces, or any of the scientific experiments. If fluid loss must be minimized or prevented on future spacecraft, the use of temperature-resistant seal and valve seat materials is recommended. Seal life can also be extended by controlling temperatures at critical sealing surfaces. Solar illumination models and television viewing of propulsion components were used in conjunction with pressure and temperature telemetry to identify failure locations.

Introduction

THE Surveyor spacecraft (Fig. 1) was designed and built by Hughes Aircraft Company under the direction of the California Institute of Technology Jet Propulsion Laboratory (JPL) for NASA. The basic over-all objectives of the spacecraft system were 1) to develop a technology for and accomplish a series of soft landings on selected areas of the surface of the moon,[1] 2) to perform experiments on a local surface area of the moon, 3) to obtain engineering data on the performance of the spacecraft system that will aid in future space exploration, and 4) to telemeter the acquired data back to earth.

Unlike many of the other subsystems on the spacecraft (Fig. 1), the vernier propulsion system (VPS)[2-4] was not designed for operability on the lunar surface; consequently, preflight mission studies included definitions of problems resulting from the probable failure of the system when subjected to the lunar environmental extremes. The VPS had been designed for the temperature range of 0° to 100°F seen during earth-lunar transit and had survived environmental tests over that range. However, lunar temperatures vary between $-250°$ and $+250°$F. The deterioration of soft fluid seals when exposed to hot propellants made leaks very probable, and such leaks could degrade the quality of scientific data by damaging thermal control surfaces (resulting in possible overheating of critical electronic components), fogging TV camera mirrors and lenses, or contaminating lunar soil (interfering with soil analysis experiments).

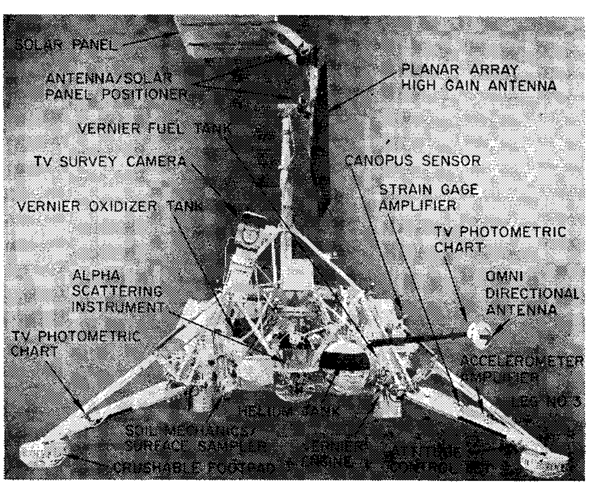


Fig. 1 Surveyor spacecraft.

Received July 7, 1969. This work was performed by Hughes Aircraft Company for the California Institute of Technology, Jet Propulsion Laboratory, under Contract JPL950056. The author would like to acknowledge the valuable discussions of data interpretation with T. B. Shoebotham of Hughes Aircraft Company and C. J. Leising of the Jet Propulsion Laboratory.

* Member of Technical Staff, Space Systems Division. Member AIAA.

Earth-based testing of these problems was limited by the difficulty of simultaneous simulation of lunar temperature and vacuum; consequently, the maximum propellant vapor concentration near critical components was estimated analytically. Specimens of various thermal control coatings, insulation materials, and optical surfaces were then exposed to the predicted concentrations of propellant vapors (first oxidizer, then fuel). Comparisons of visual appearance, weight, optical transmission, solar absorptance, and emittance were made before and after exposure. The tests showed that any changes were less than those allowed from in-flight exposure to ultraviolet radiation; and consequently, propellant leakage was judged nondetrimental to spacecraft components. Lunar soil contamination was not simulated; however, any leakage would be rapidly dissipated by the combined effects of the high temperature and low pressure.

The instrumentation that was used to assess VPS in-flight and lunar-day performance consisted of: 1) pressures in the helium tank (P_{He}), oxidizer tank system (leg 3, P_{ot_3}), and the fuel tank system (leg 2, P_{ft_2}); and 2) temperatures in the He tank (T_{He}), the 6 propellant tanks (located on bottom near propellant outlet, T_{ot_i} and T_{ft_i}), the 12 propellant feed lines (T_{ol}'s and T_{fl}'s) to thrust chamber assemblies, and the 3 thrust chamber assemblies (on regenerative cooling jacket, T_{e_i}).

The fuel and oxidizer tanks (3 each) were of equal volume, one pair supplying each engine. Each tank contained a teflon expulsion bladder to permit positive propellant control under zero-g conditions. The oxidizer was MON-10 that is composed of mixed oxides of nitrogen, 90% N_2O_4 and 10% by weight NO to depress the freezing point. The fuel was monomethyl hydrazine monohydrate (MMH). These propellants ignite hypergolically when mixed.[4] The arrangement of the tanks on the spaceframe is illustrated in Fig. 2. Propellant freezing or overheating during earth/lunar transit was prevented by a combination of active and passive thermal controls, utilizing surface coatings, multilayered blankets, and electrical and solar heating. The propellant tanks were thermally isolated from the spaceframe.

Helium was released to the propellant tanks prior to the midcourse maneuver by activating a squib-actuated helium release valve. A downstream single-stage regulator then maintained the propellant tank pressure at 730 psi during thrusting. Helium check and relief valves were located in a separate package on the spaceframe and were connected by a single line to the helium tank and high-pressure valves assembly. The check valves prevented the back flow of helium and propellant vapors to the pressure regulator or between fuel and oxidizer tanks; the relief valves relieved excess pressure from the propellant tanks in the event of a malfunction of the helium pressure regulator or propellant tank overheating.

The thrust chambers were located near the three landing leg hinge points. Engine 1 could be rotated $\pm 6°$ about an axis in the spacecraft X-Y plane for spacecraft roll control, but engines 2 and 3 were not movable. The thrust of each engine (which was monitored by strain gages installed on each engine mounting bracket) could be throttled over a range of 30 to 104 lb.

Postlanding Results and Discussion

Since pressure and temperature data were frequently insufficient to isolate offending components and/or failure modes, several auxiliary data sources were employed. Table 1 summarizes the failure experiences.

Approximately 9 min after the lunar touchdown of Surveyor I, the remaining He was vented to reduce the probability of propellant expulsion onto the lunar surface.[5] The sun's position was such that the leg 1 propellant tanks and thrust chamber assembly (TCA) were shadowed, and the leg 2 and 3 propellant tanks, lines, TCAs, and the helium tank illuminated. (As the sun rose and set, this situation was reversed.) Radiant heating caused the oxidizer pressure (P_{ot3}) to increase (Fig. 3); 22 hr after touchdown, the oxidizer relief valve automatically relieved for the first time. Over

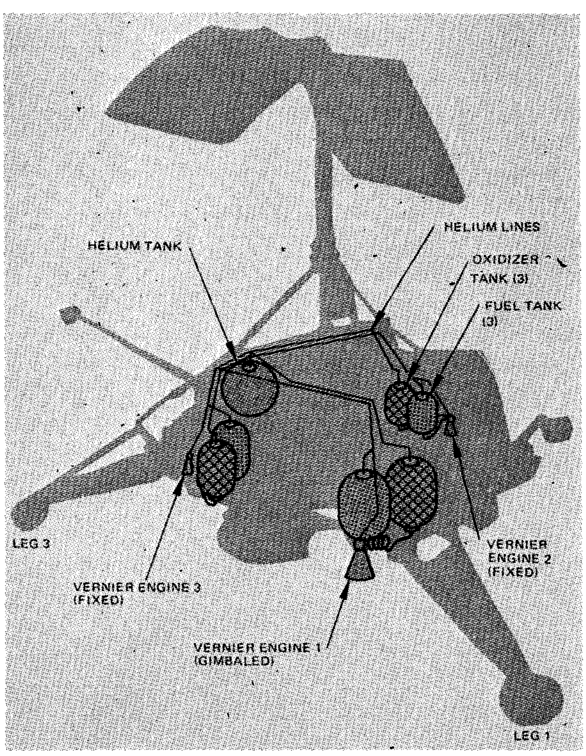


Fig. 2 Vernier propulsion system installation.

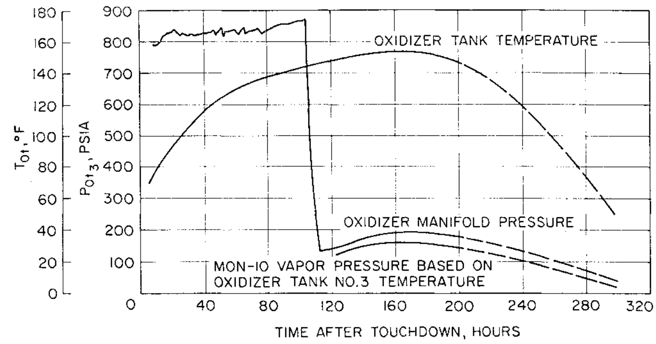


Fig. 3 Oxidizer pressure and tank temperature history—Surveyor I.

the next 78 hr, the valve cycled 9 times as the propellant continued to vaporize. After the ninth cycle, P_{ot3} began to drop and continued to fall for 8 hr, and the temperatures of all 3 oxidizer tanks dropped due to propellant cooling by vaporization.

During lunar operation, the oxidizer relief valve had opened at pressures between 825 and 865 psia and reseated between 817 and 825 psia. The acceptance test records indicated that the valve opened at 827 psig and reseated at 810 psig. Since the relief valves were attached to the top of the He tank in the full sun and were isolated from the mass of the tank shell through a threaded connection, they were significantly hotter than the 140°F indicated by the nearest temperature sensor (on the shaded part of the tank); therefore, the relief valve malfunction was attributed to degradation of the seat material caused by the combined effects of high temperature and oxidizer vapor exposure. Temperatures seen by the various components are given in Table 2.

Late in the first lunar day, and again in the second, P_{ot3} stabilized at values corresponding to the vapor pressures expected from temperature data. The data indicated the relief valve had reseated, since an open valve would have allowed MON-10 vapor to diffuse through the bladder until P_{ot3} fell to zero.

The feasibility of firing the VPS to test lunar soil cohesiveness under jet impingement conditions was investigated late in the lunar day. The VPS was found to be functional; however, the low engine inlet pressure would cause the thrust levels to be below nominal. After an evaluation of all possible problems, the firing was cancelled because of the risk of depositing dust on the spacecraft thermal finishes and lenses.

Experience gained on Surveyor I showed that the VPS would remain operational for a sufficient period during the lunar day to allow it to be used to:

1) Test lunar surface cohesiveness; these data would help define the problem of formation of dust clouds that could interfere with radar control during landing and deposit dust on sensors, windows, and thermal finishes.

2) Change the spacecraft location to allow stereoscopic views by the TV camera, soil analysis of varying surfaces, and TV views of the effect of the impact of the spacecraft landing pads on the original site.

The desirability of these added capabilities stimulated investigations of techniques to extend VPS life. In the relief valve tests, lunar temperatures, and exposure times were simulated without valve malfunction or failure. However, lunar vacuums and temperature gradients were not simulated, and the exact cause of relief valve failures was not determined.

The subsequent in-flight failure of Surveyor II due to VPS malfunction resulted in the addition of a pressure sensor on the fuel side on Surveyor III. After resolution of a postlanding data anomaly, all Surveyor III propulsion parameters were found to be similar to those seen on Surveyor I.[6] Since a lunar translation of the spacecraft was under consideration,

Table 1 Summary of VPS failures after landings of Surveyors I, III, V, VI, and VII

No.	TBF[a]	Failure type	Telemetry indications	Probable cause
I	104 hr	Gas leak through MON-10 relief valve	1) Rapid loss of P_{ot} and P_{He} 2) Slow drop of ~20°F in T_{He} and T_{ot} 3) 25°F increase in MON-10 line temperature, indicating flow from hot engines to cooler tanks as tanks depressurized	Oxidizer (MON-10) relief valve seat failed because of exposure to hot vapors
III	165 hr	Gas and/or liquid leak on MON-10 side	1) Rapid loss of P_{ot} and P_{He} 2) Drops in T_{e_1} and T_{ol_1} indicating flow through MON-10 shutoff valve at engine	MON-10 shut-off valve failed due to exposure to hot MON-10
V	178 hr	Liquid MON-10 leak at tank 1 followed by gas leak	1) Loss of P_{ot} and P_{He} 2) 100°F drop in T_{ot_1} 3) 20°F drop in retro attach bolt 1 temperature 4) TV photos showed that mylar wrap on MON-10 tank 1 had been pressurized, and its cooldown rate after sunset was greater than those for other two MON-10 tanks	O-ring on oxidizer tank 1 degraded by hot liquid MON-10
V	273 hr	Gas leak on fuel side	1) Loss of P_{ot} 2) Second lunar day T_{ot}'s indicated that liquid fuel had not leaked from tanks	Undetermined whether failure occurred at fuel relief valve, TCA solenoid valve, or a gas-side O-ring in a fuel tank
VI	228 hr	Liquid oxidizer leak at tank 1 followed by gas leak	1) ±10°F fluctuation in T_{ot_1} 2) Loss of MON-10 and He pressure 3) Cooldown rate after sunset was greater for this MON-10 tank than for the other 2	O-ring on MON-10 tank 1 degraded by hot liquid
VII	91–191 hr	Erratic cycling and leakage at MON-10 relief valve	1) Exposure to sun on 11th vent cycle caused deviations in MON-10 relief valve's crack and reseat pressures; after 12 cycles, P_{ot} began to decay 2) Leak stopped after relief valve was reshadowed by repositioning planar array antenna	Distortion and degradation of valve's seat and differential thermal expansion caused erratic behavior and leakage when valve was hot
VII	260 hr	Liquid fuel leak at engine 2	1) Rapid 90°F drop in T_{e_2} as fuel vaporized and cooled engine 2) T_{fl_2} was raised by warm propellant 3) Pressure and temperature data and tank cooldown rates after sunset indicated liquid leakage	Fuel poppet in engine 2 shut-off valve failed due to seat degradation after exposure to hot (288°F) fuel
VII	270 hr	Oxidizer check valve sticking	1) P_{ot} fell below He regulator pressure; correct regulator operation confirmed by P_{ft} data	Check valve seat degradation after exposure to hot MON-10
VII	324 hr	Continuing gas side leak on fuel side	1) Pressure and temperature data indicated continued loss of pressurant from fuel side	Gas leakage through engine 2 fuel poppet after liquid leak depleted fuel not yet frozen in tank
VII	335 hr	Loss of liquid from MON-10 tank 3	1) Cooldown data indicated tank 3 liquid content to be normal at sunset, but that later tank was nearly empty 2) Increase in T_{ot_3} decay rate indicated large reduction of tank thermal capacity; $T_{ot_3}(t)$ profile during propellant freezing indicated little oxidizer remaining	Leak at liquid side O-ring after O-ring was degraded by hot oxidizer

[a] TBF = time before failure, from landing time.

P_{He} was not vented at lunar landing, and it slowly increased as T_{He} rose, until a solar eclipse occurred during the fifth earth day of lunar operations. By then, the translation maneuver had been vetoed, so P_{He} was relieved.

The oxidizer relief valve vented approximately 14 times during the lunar day. As on Surveyor I, the crack and reseat pressures increased with exposure to the lunar environment; P_{ot_3} began to fall 165 hr after touchdown and stabilized 45 hr later. Simultaneous drops in T_{ol_1} and T_{e1} indicated that the pressure loss was due to oxidizer liquid leakage through that engine. The system parameters were not monitored beyond 215 hr after touchdown, since the pressure loss had rendered the VPS inoperable. The leak had no observable effect on the spacecraft thermal finishes or lenses.

Surveyor IV was in the terminal stages of a soft-landing when contact with the spacecraft was lost and not regained. This failure prevented acquisition of lunar day data.

An earlier helium regulator malfunction caused P_{ot_3} and P_{ft_2} on Surveyor V to be approximately the same as P_{He}[7]; the helium remaining in the helium tank was not vented, because firings to determine lunar surface cohesiveness were under consideration. Subsequent pressure increases due to lunar heating allowed a successful static firing (without spacecraft translation) 55 hr after touchdown. At 181 hr after landing, P_{ot_3} began to drop and decayed from 812 to 328 psia

Table 2 Surveyor I VPS temperatures during first lunar day

Component	Touchdown,[a] °F	Maximum,[a] °F
Thruster jackets	383/355/314[b]	245/228/224
Propellant feedlines	79.5/62.2/75.8	221/201/185
Fuel tanks	66.2/51.8/67.7	190/164/171
Oxidizer tanks	59.7/43.2/57.3	174/166/154
Helium tank	44.3	140

[a] Temperatures for the three thruster systems are given in order 1/2/3.
[b] Postshutdown temperature.

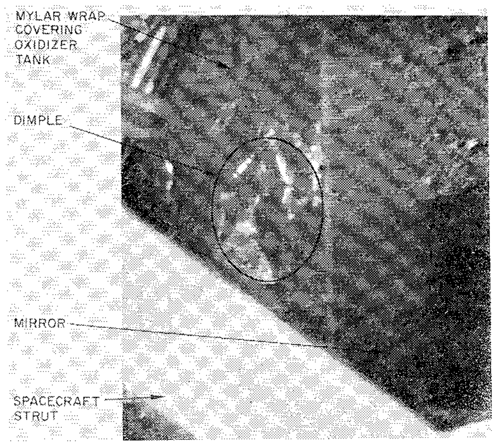
over a period of about 55 hr. P_{ot_3} had stabilized 57 hr later and thereafter corresponded to the vapor pressure in the leg 3 tank. Concurrent with the pressure decrease, a 100°F drop in T_{ot_1} and a 30°F drop in T_{ol_1} occurred. These data are consistent with a liquid propellant leak through the leg 1 oxidizer tank O-ring seal. In addition, TV photographs† (Fig. 4) illustrate that portions of the mylar insulation on oxidizer tank 1 were inflated at approximately the time of pressure loss. Of the seals near the base of this tank, only the O-ring was enclosed within the mylar wrap, and only leakage at that location could have caused the mylar insulation to inflate. (The mirror shown in Fig. 4 was attached to the spacecraft structure to allow TV pictures of the lunar terrain beyond the field of view of the camera. The two photographs of the mirror reflect the moving spacecraft shadow and the changing appearance of the lunar surface as the lunar day proceeds from morning to afternoon.) Special tests simulating the lunar day profile for T_{ol_1} showed that at $T_{ol_1} \geq 160$°F, the O-ring material (Viton A) is severely attacked by the oxidizer, whereas very little degradation occurred over the temperature range seen during the earth-lunar transit.

Helium pressure remained approximately constant until 275 hr after landing, when a fuel pressure decrease was noted. As the fuel system leaked gas, the helium tank was vented through the fuel system, causing both to reach zero pressure simultaneously about 20 hr later. Since no temperature changes accompanied this pressure drop, it was concluded that the leakage was from the gas side of the fuel system. The relief valve, propellant tanks, and vernier engine solenoid valves were all possible leakage points. The seals on any of these components could have failed because of the high-temperature environment.

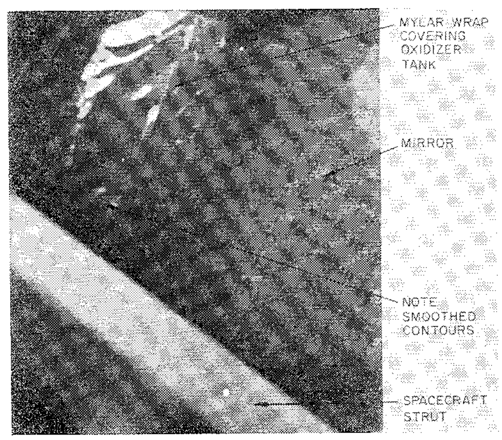
For Surveyor VI, P_{He} was not vented at landing, because operations requiring the VPS were planned.[8] Both P_{ot_3} and P_{He} began to increase due to lunar heating, and the oxidizer relief valve cycled 5 times at 6- and 8-hr intervals. The solar panel was repositioned in an effort to shade the relief valves; this was the first use of the movable panels to provide active component shading. Relief valve shadowing was confirmed by television monitoring and allowed a subsequent spacecraft liftoff and translation.[9]

At 231 hr after landing, P_{ot_3} began to drop rapidly, falling from 806 to 738 psia in less than 3 hr. The magnitude of this drop and the absence of any significant cooling on the propellant tanks, lines, and engines indicated that the leak was gaseous. The regulator then opened and allowed He to flow into the oxidizer tanks until P_{ot_3} stabilized at the oxidizer vapor pressure. To determine the cause of the gas leak, temperature data were studied. To separate the effect of shading from effects of leakage on spacecraft temperatures, a $\frac{1}{5}$-scale model of Surveyor was illuminated by a collimated light source. The observed shadow patterns indicated that the small T_{ot} fluctuations observed 31 hr prior to the P_{ot_3} loss were not caused by shading from other spacecraft components and were therefore the result of fluid leakage through the O-ring seal. This seal lasted 50 hr longer than the Surveyor V seal because it reached only 180°F as compared to

† These pictures represented the first use of TV camera as an aid in VPS failure mode determination.



a) Day 225 GMT



b) Day 258 GMT

Fig. 4 Changes in surface of oxidizer tank insulation between lunar morning and afternoon—Surveyor V.

193°F on Surveyor V. The other oxidizer tanks on both spacecraft were significantly cooler; their seals showed no evidence of failure.

To estimate the amount of oxidizer leakage, the amount of propellant remaining at sunset was estimated from the cooling rate of the propellant and tank. Since the lunar surface temperature fell from +250° to −250°F rapidly, compared to the temperatures of the insulated tanks, the lunar surface behaved as a nearly uniform heat sink for radiant heat transfer. Estimated T_{ot}'s on Surveyors I, V, and VI are plotted vs time after sunset in Fig. 5. The knees in the curves from 0

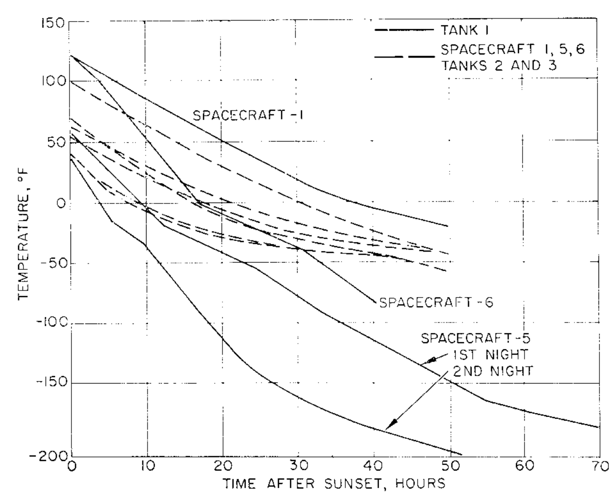


Fig. 5 Oxidizer tank temperatures after lunar sunset—Surveyors I, V, and VI.

to $-50°F$ resulted from binary freezing of the oxidizer. Each of the 9 tanks had approximately 5 lb of oxidizer remaining at touchdown and would, therefore, be expected to have similar cooling profiles at sunset if there were no propellant usage or leakage. However, oxidizer tank 1 on Surveyor VI cooled very much like the nearly empty tank on Surveyor V, and in a significantly different manner from that of the other tanks. The amount of oxidizer remaining was calculated from both cooling and freezing data. The calculations correlated and indicated that approximately 4 lb of oxidizer had been lost. Oxidizer tank 1 on Surveyor V subsequently showed an increased rate of cooling at the second lunar sunset, indicating further propellant loss during the second lunar day.

In summary, all available data confirm that a liquid leak occurred on the Surveyor VI oxidizer tank 1 prior to the rapid gas leak. Such liquid losses could produce engine starvation during a lunar translation maneuver, and the resulting uneven torques could cause catastrophic loss of attitude control.

Surveyor VII landed near the crater Tycho, with legs 2 and 3 facing NE and NW, respectively.[10] The southern latitude resulted in low sun angles and minimized the possibilities of using the solar panel and planar array to shade spacecraft components. The increased exposure to radiation caused the tank and engine temperatures on legs 2 and 3 to be more than 20° hotter than on previous spacecraft. On leg 2, the maximum oxidizer tank, fuel tank, and engine temperatures were 210°, 226°, and 290°F, respectively. The same components on leg 3 reached 190°, 210°, and 280°F, respectively.

During the first 10 cycles, the oxidizer relief valve operated normally, cracking at approximately 850 psi and reseating at approximately 830 psi. The valve was then exposed to the sun and heated to about 300°F during the 9th and 11th vent cycles. On the 11th vent cycle, the relief valve began to act as erratically as on previous spacecraft. Soon thereafter, P_{ot_3} began to vary in a manner inconsistent with P_{ft_2} and P_{He}. These pressure fluctuations could have been caused by the oxidizer check valve being stuck in an almost closed position, which could result from the earlier high temperatures and back pressures which might have deformed the seat and caused the valve to bind, severely restricting its travel. Before sunset, P_{ot_3} dropped from 766 to 452 psi in 1.4 hr. None of the temperature drops previously associated with a liquid leak were noted prior to or during this pressure loss; therefore, the likely source of the leak was the relief valve, which had finally failed due to seat erosion. Study of T_{ot} histories indicated that the initial rate of cooling of oxidizer tank 3 was similar to that of a tank with approximately 5 lb of residual oxidizer; however, soon after sunset, the cooling rate increased to that of a tank containing only 1 or 2 lb of oxidizer. This phenomenon could be explained by a liquid leak during this period, which was subsequently confirmed by the short freezing time of the remaining oxidizer. As on Surveyors V and VI, the leak probably occurred at the O-ring seal at the base of the tank.

Late in the lunar day, the fuel system also experienced liquid and gas leakage. At 55 hr before sunset, T_{e_2} fell 88° as liquid fuel leaked into the vacuum, vaporized, and cooled the engine. Simultaneously, T_{fl_2} increased as hot fuel flowed from the tank to the engine and warmed the line. Shadow plots and sun illumination simulations on scale models confirmed that these temperature fluctuations were not caused by shadowing. The probable cause of the liquid leak was a degraded fuel poppet on the thrust chamber assembly; JPL has demonstrated that poppets on shutoff valves are chemically attached and degraded by hot fuel.[11] The leak subsided near sunset when falling fuel system temperatures caused the fuel to become very viscous. A gas leak developed in the fuel system soon after sunset and continued until loss of data. The leakage could have been through either the fuel relief valve or an engine solenoid valve.

Concluding Remarks

All VPSs lost oxidizer and/or fuel pressure during the first lunar day. If it is desirable to minimize or prevent long-term fluid leakage from future spacecraft, Surveyor experience points to the use of temperature-resistant seal materials and/or positive temperature control techniques. The Hydraulic Research Corporation is currently developing propellant valves which employ tungsten carbide seats to allow repeatable sealing for 5 years at elevated temperature (>250°F). Soft-seal life at high temperature can be increased by use of fluorocarbons (300–400°F) rather than the nylons (200–300°F) in widespread usage. Optional temperature control techniques are: 1) passive thermal control by surface finishes, special shading by fixed plates or shields, thermal wrappings, and location of seal bearing components to take advantage of natural shading from other components; and 2) active thermal control by shading from movable spacecraft components, and electrical heating as required.

The evaluation of propulsion system lunar surface status and the determination of failure modes are aided by the use of the following tools and techniques: 1) instrumentation (pressure sensors on each independent subsystem and temperature sensors at each potential leakage location); 2) shadowplots and scale-model solar simulations to predict temperature history and allow temperature changes due to normal shading to be isolated from those caused by leakage; 3) television photography to confirm shading attempts and verify suspected leakage locations; and 4) monitor temperatures past sunset to allow residual propellant quantities to be estimated from the heat transfer to the rapidly changing thermal environment.

References

[1] Ribarich, J. J., "Surveyor Spacecraft Landing Accuracy," *Journal of Spacecraft and Rockets*, Vol. 5, No. 7, July 1968, pp. 768–773.

[2] Ellion, M. E., DiCristina, H., and Maffei, A. R., "Development of the Surveyor Vernier Propulsion System," *Journal of Spacecraft and Rockets*, Vol. 4, No. 3, March 1967, pp. 339–346.

[3] Wrobel, J. R. and Grelecki, C., "Surveyor Vernier Engine Fuel Blend—a Constrained Optimization," *Journal of Spacecraft and Rockets*, Vol. 4, No. 3, March 1967, pp. 347–353.

[4] McDermott, C. E., Breshears, R. R., and McCafferty, J., "Dynamic Performance of Surveyor Throttleable Engine When Propellants Contain Dissolved Helium," *Journal of Spacecraft and Rockets*, Vol. 4, No. 5, May 1967, pp. 669–673.

[5] Cloud, J. D., Beall, K. C., and Leuschner, R. H., "Surveyor I Flight Performance—Final Report," SSD 68223R, Vol. III, Sec. 5.7, Oct. 1966, Hughes Aircraft Co., Culver City, Calif.

[6] Cloud, J. D., Van Horne, T. B., and Leuschner, R. H., "Surveyor III Flight Performance—Final Report," SSD 68189-3, Sec. 5.6, July 1967, Hughes Aircraft Co., Culver City, Calif.

[7] Cloud, J. D., Van Horne, T. B., and McIntyre, W. B., "Surveyor V Flight Performance—Final Report," SSD 68189-5 Sec. 5.6, Nov. 1967, Hughes Aircraft Co., Culver City, Calif.

[8] Cloud, J. D., Van Horne, T. B., and McIntyre, W. B., "Surveyor VI Flight Performance—Final Report," SSD 68189-6, Sec. 5.6, Jan. 1968, Hughes Aircraft Co., Culver City, Calif.

[9] Pfund, E. T., "A Case Study in Real-time Ground Control and Data Processing," *Journal of Spacecraft and Rockets*, Vol. 6, No. 1, Jan. 1969, pp. 9–17.

[10] Cloud, J. D., Van Horne, T. B., and McIntyre, W. B., "Surveyor VII Flight Performance—Force Report," SSD 68189-7, Sec. 5.6, March 1968, Hughes Aircraft Co., Culver City, Calif.

[11] Leising, C. and Stocky, J., "SC-VII Propulsion System Performance During First Lunar Day," Interoffice Memo SP/SA 165, Feb. 27, 1968, Jet Propulsion Lab.