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Mars Pathfinder Rover Egress Deployable Ramp Assembly

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Brian R. Spence* and Lee F. Sword**

Abstract

The Mars Pathfinder Program is a NASA Discovery Mission, led by the Jet Propulsion Laboratory, to launch and place a small planetary Rover for exploration on the Martian surface. To enable safe and successful egress of the Rover vehicle from the spacecraft, a pair of flight-qualified, deployable ramp assemblies have been developed. This paper focuses on the unique, lightweight deployable ramp assemblies. A brief mission overview and key design requirements are discussed. Design and development activities leading to qualification and flight systems are presented.

Mission Overview

The Mars Pathfinder Program is a NASA Discovery Mission, led by the Jet Propulsion Laboratory, to launch and place a small planetary Rover, dubbed Sojourner, for exploration on the Martian surface. To enable safe and successful egress of the Rover vehicle from the spacecraft, a pair of flight-qualified, lightweight deployable ramp assemblies are utilized. Figure 1 depicts an artist rendition of the Mars Pathfinder spacecraft, Rover, and its deployable ramp assemblies, as they would appear on Mars.

The Mars Pathfinder spacecraft is scheduled for launch in December, 1996, for a subsequent rendezvous with Mars in July, 1997. During final descent to Mars, large inflatable airbags will be pressurized to encapsulate the spacecraft and reduce the overall landing impact with the Martian surface. Once landing has been achieved, the airbags will be deflated and retracted to allow for the opening of three spacecraft petals. Each petal is populated with a complement of solar cells, which provide spacecraft power once they are completely opened and exposed to sunlight.

The Rover vehicle and the deployable ramp assemblies are stowed to one of these petals during the entire journey to Mars. After the airbags have been completely retracted, the two ramp assemblies are deployed by severing two circumferentially wrapped tie-down cables with pyrotechnic cutters. Once deployed, the ramp assemblies provide a safe and successful Rover egress path from the spacecraft to the Martian surface.

* Astro Aerospace Corporation, Carpinteria, CA
** Jet Propulsion Laboratory, Pasadena, CA

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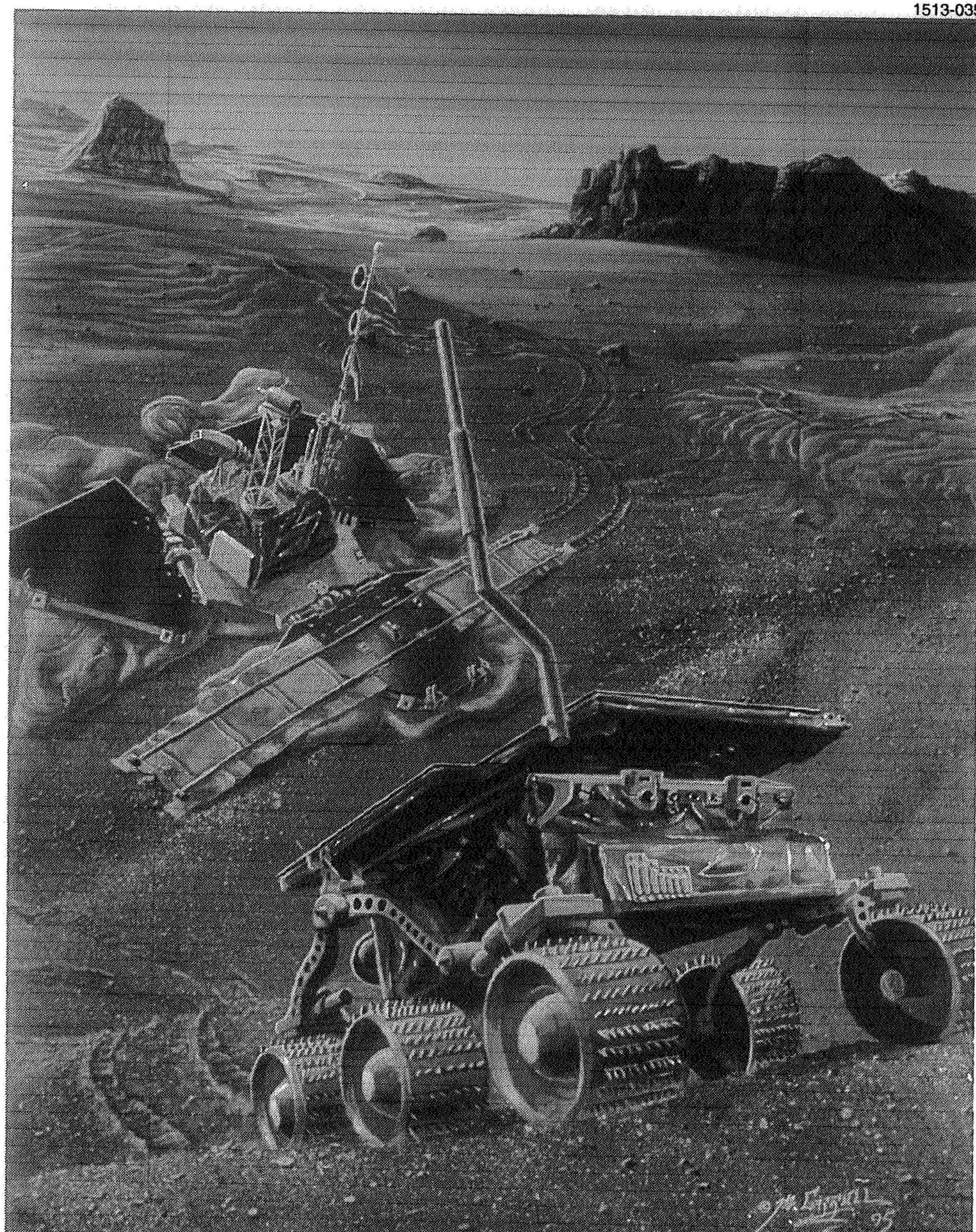

Figure 1. Mars Pathfinder Spacecraft, Rover and Deployable Ramp Assemblies.

Key Design Requirements

Design requirements of space hardware for interplanetary mission applications are generally much more demanding than typical Earth-orbit applications. The deployable ramp assembly had many of its own unique requirements, ranging from operability, loading, stowed and deployed envelopes, weight, schedule, and cost. A listing of the key design requirements are shown in Table 1.

Table 1: Key Design Requirements

Programmatic:	1.	Better, faster, cheaper
Operability:	1.	Provide reliable deployment at +50°C to -140°C.
	2.	Provide reliable deployment at a ±30° inclination to the local horizontal in all orientations.
	3.	Design capability for multiple deployments.
	4.	Provide guiding features for Rover vehicle during egress.
Loading:	1.	Sustain a 66-g level centrifuge loading for a duration of 1 minute in each of the three orthogonal axes.
	2.	Sustain a low-level random vibration launch spectrum.
	3.	Support a Rover weight of 12.5 kg (27.55 lb) at ramp mid-span without buckling while simply supported at ends.
	4.	Provide ramp buckling in a cantilevered condition when Rover is translated between 1/3 and 2/3 of its distance down the ramp.
Envelope:	1.	Stowed package to fit within a constrained compact trapezoidal volume.
	2.	Minimal deployed footprint which does not obscure petal-mounted solar cells.
Weight:	1.	Ramp assembly weight ≤1000 g (2.20 lb)
Schedule:	1.	Eight-month design, development, production, and test of one qualification unit, two flight units, and one flight spare unit.

Flight System Description

The Mars Pathfinder Rover Egress Subsystem consists of two deployable ramp assemblies: one fore and one aft of the translation direction (Figure 1). When deployed, the ramp assemblies measure approximately 136 cm (53.5 inches) in length by 42 cm (16.5 inches) wide and allow for safe and successful Rover egress. Figure 2 depicts the ramp assembly in the deployed configuration.

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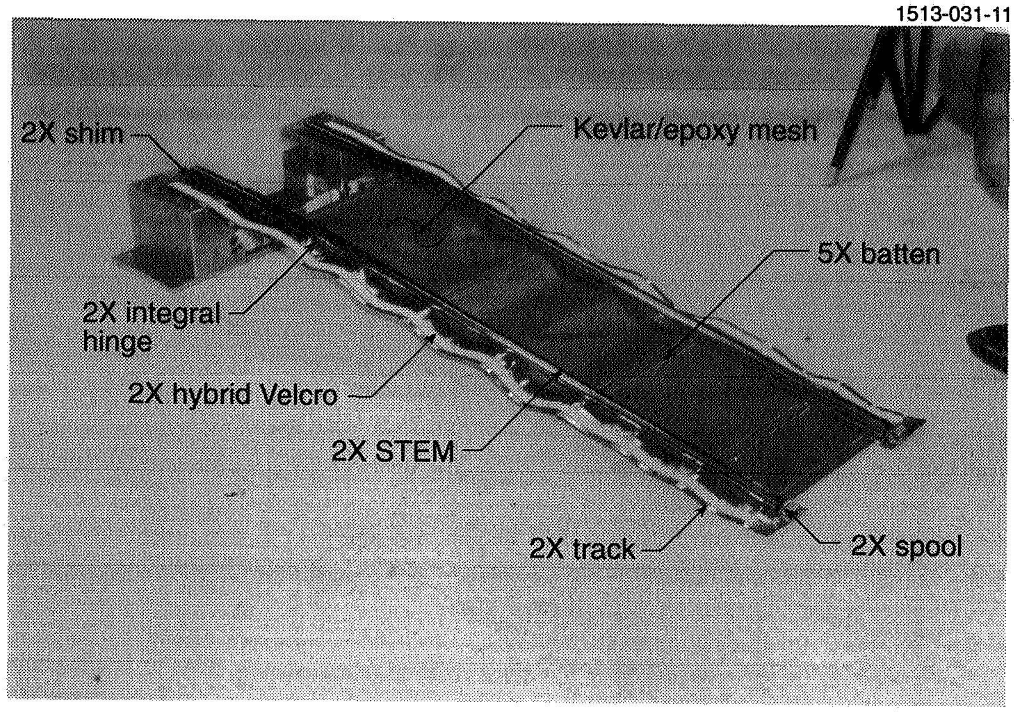

Figure 2. Deployed Ramp Assembly.

The flight deployable ramp assembly consists of two nested pairs of 2.18-cm (0.86-inch) diameter Astro STEM™ (Storable Tubular Extendible Member) stainless steel elements, which together provide the required strength, stiffness, and deployment force. Five aluminum alloy battens are attached to each STEM™ element along their lengths to maintain precise separation between elements, thus enabling the Rover to straddle them safely during translation. During egress, the Rover utilizes the outboard surface of each STEM™ element as an inboard curb for guiding purposes. Thin stainless steel tracks, located on the outboard side of each element, provide for a Rover wheel rolling surface. The tracks are attached to the STEM™ elements and battens by screws and rivets, respectively. When attached, the tracks play a large role in reacting all in-plane shear loads. A lightweight Kevlar/epoxy open-weave mesh completely covers the mid-span of the ramp over most of its entire length. The Kevlar/epoxy mesh helps prevent excess airbag material and other potential hazards from protruding significantly above the translation plane, where possible impediment to Rover egress could result. The Kevlar/epoxy mesh is attached and sandwiched between the elements and track and pocketed for restraint at each batten. A cylindrical spool is mechanically attached to the outboard tip of each track and centered in-line with each STEM™ element. The spools assist the initial stowage process during roll-up of the ramp assembly. The inboard end of each STEM™ element is fastened to a shim, which provide the mechanical interface with the spacecraft petal. Continuous strips of stainless steel/nylon hybrid Velcro™ are adhered to the outer sides of the top and bottom surfaces of the tracks. The hybrid Velcro™ provides kinematic coordination and control during deployment.

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Figure 3. Stowage Process.

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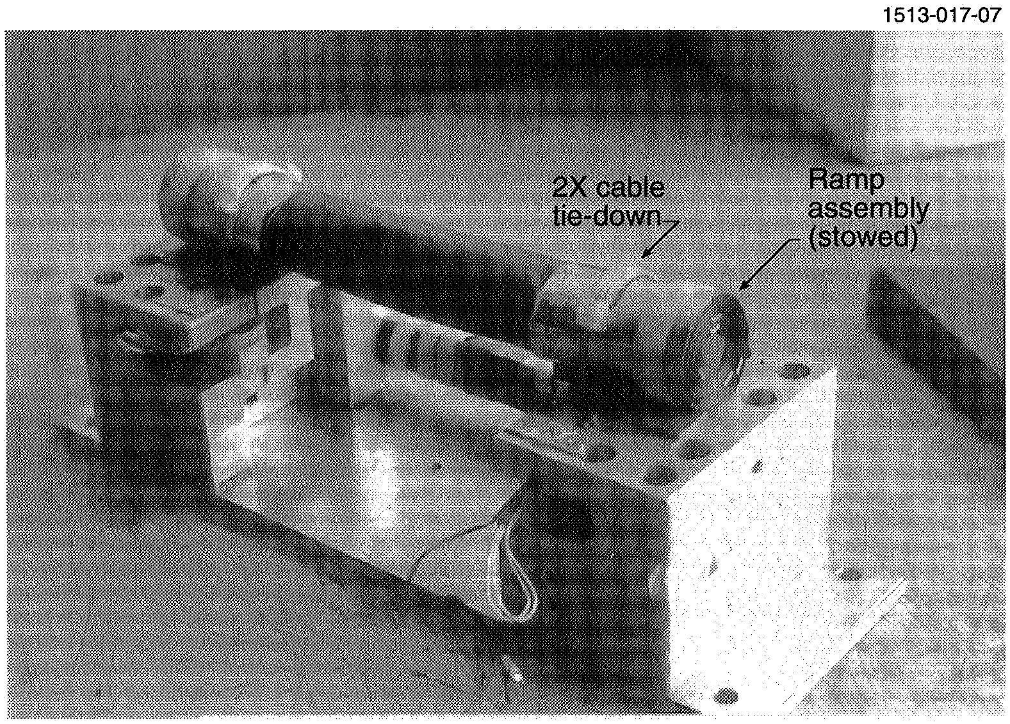

Figure 4. Stowed Ramp Assembly.

When stowed, each ramp assembly is rolled up in a compact cylindrical envelope of approximately 7.62 cm (3.0 inches) in diameter by 42 cm (16.5 inches) in length. Figure 3 depicts the stowage roll-up process. The cylindrical package is tied down to the spacecraft petal structure with two cables located on each side of the roll. Figure 4 depicts the ramp assembly in the stowed configuration. The cable tie-downs circumferentially preload the stowed package against the spacecraft petal for launch. Deployment is initialized by the simultaneous severing of the two preloaded cables with pyrotechnic cable cutters. Immediately after cable severance, the ramp unfurls to its deployed position in less than 1 second. The entire deployment sequence is shown in Figure 5.

Discussion

<u>The Proposal Phase</u>

This program proved to be much more involved than a routine design and development exercise of what was originally deemed as a simple deployable structure. As part of the initial proposal effort, Astro successfully produced and tested, albeit to less stringent requirements, a breadboard demonstration model in an effort to mitigate any perceived program risk. The breadboard unit appeared to satisfy the majority of requirements and was envisioned to require only slight modifications to fulfill compliance. However, as will be presented, what worked so well as a breadboard model eventually required some significant modifications in the design and manufacture to completely satisfy all the requirements.

In total, four development units were built and tested until an acceptable flight design was produced. The breadboard model, developed for proposal purposes, was literally thrown together in a matter of hours and assembled with bits of hardware salvaged throughout the shop. Items, such as used STEM™ elements, aluminum mesh screen, and soft rivets were integrated with large manufacturing tolerances. Unlike the qualification and flight units, the breadboard model had only one STEM™ element per side. At the time of the proposal, it was felt that this configuration could potentially satisfy the buckling/deflection requirements with or without slight modification. The model underwent many successful deployments under a variety of conditions prior to contract award and had lived beyond expectations. As a result, the breadboard model laid the basis for qualification design.

<u>Breadboard to Qualification</u>

Once the program was underway, it was evident that the breadboard configuration, with one STEM™ element per side, was not going to meet the simply supported and cantilevered deflection loading requirements. Therefore, for the development unit design, an additional STEM™ element was added to each side of the ramp assembly. The incorporation of two elements per side was not perceived to be a concern but turned out to create some major difficulties.

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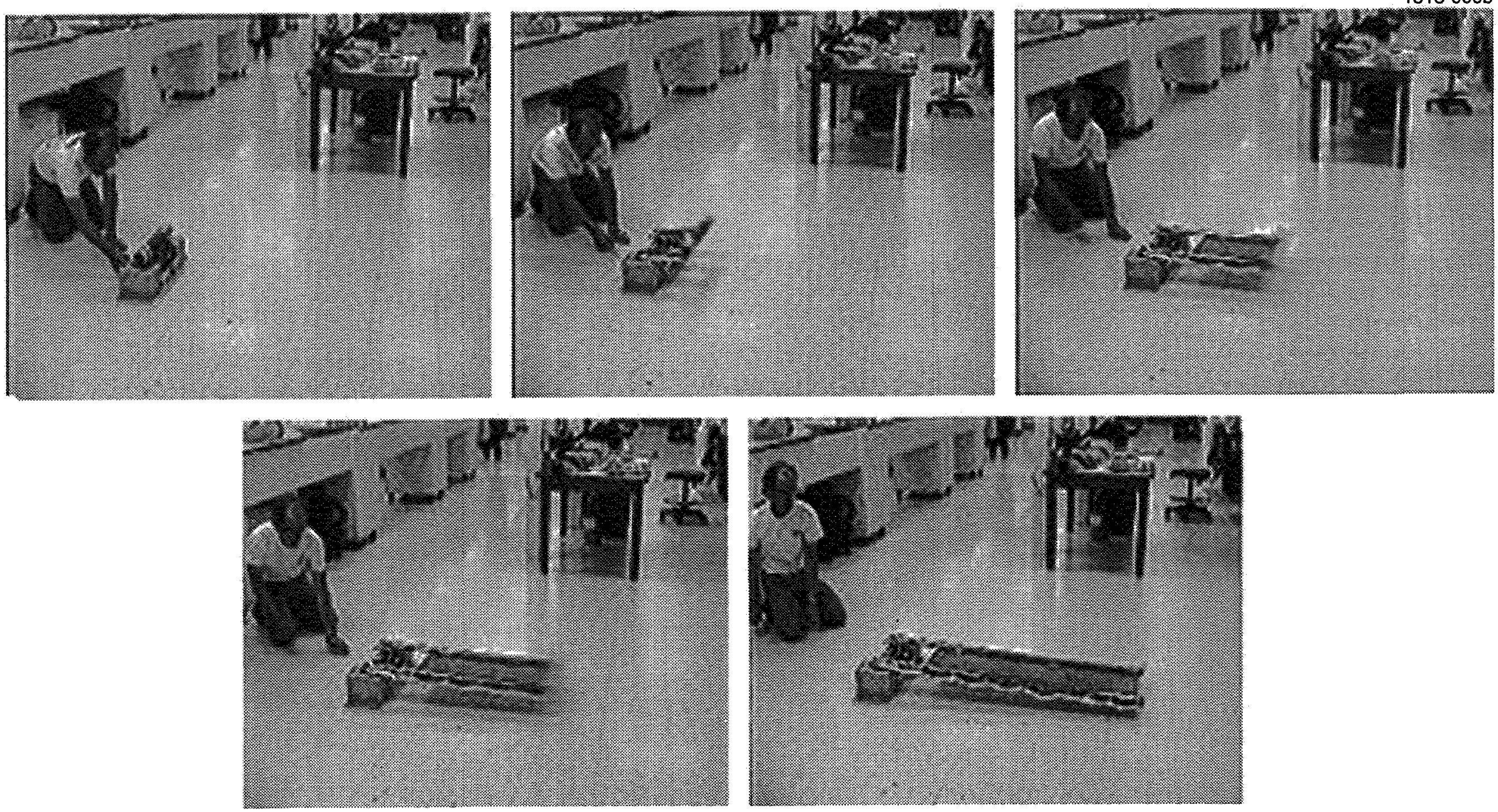

Figure 5. Deployment Sequence (Controlled and Coordinated).

The addition of another STEM™ element to the design resulted in three rigid items (the inner STEM™ element, the outer STEM™ element, and the track) that needed to be tightly rolled on top of one another to create a compact stowed package. The additional STEM™ element was integrated into the design without allowing for mechanical compliance between the individual elements and track.

When the first development unit was produced and subsequently rolled up to its stowed configuration, it did not conform into a neatly oriented nested roll. Inspection showed that each element was not in intimate contact with one another. Rather, there were diametric discontinuities on practically every wrap, thus resulting in localized deformation along the elements near each rivet attachment point. Figure 6 shows an end view of the development unit stowed package with diametric discontinuities.

During the stowage procedure, it was evident from the physical effort required that the nested STEM™ elements were constraining each other for position. As a result, some rivets at discrete attachment points were totally or partially sheared, and some elements had elongated notches in need of mechanical compliance. Because the nested components being rolled up had no functional features to provide any mechanical compliance, damage to the ramp assembly resulted after every stowage and deployment cycle. With no built-in mechanical compliance, the STEM™ elements could only withstand approximately four to five cycles before needing replacement. In some instances, the STEM™ elements were so damaged that they experienced local deformation, tearing, and loss of spring force in critical regions, thus contributing to unacceptable deployments.

To alleviate the interference problem, elongated slot features were ultimately machined into each STEM™ element at the attachment points. The track incorporated a wave between attachment points to provide additional length to allow for diametric compliance between all the nested components. The unit was re-assembled, then subsequently stowed. Inspection of the stowed package yielded a tightly wrapped, uniform roll with elements nested in intimate contact with one another, as shown in Figure 7. Subsequent designs, incorporating mechanical compliance features, yielded no component damage and produced the ability for the hardware to sustain multiple deployments.

Complex Deployment Kinematics

Because of the "better, faster, cheaper" characteristics of this program, time and efficiency were of the essence. In the infancy stages of the program, prior to any real engineering layout work, a mechanical interface was agreed upon. As a result, the allotted stowed envelope turned out to be much more difficult to meet, once engineering and testing activities were underway. To fit within the envelope, the ramp assembly, particularly the STEM™ elements, had to be rolled up to a much tighter diameter than was comfortable. The smaller stowed diameter in the development unit resulted in more stored energy in the stowed configuration than its breadboard model predecessor.

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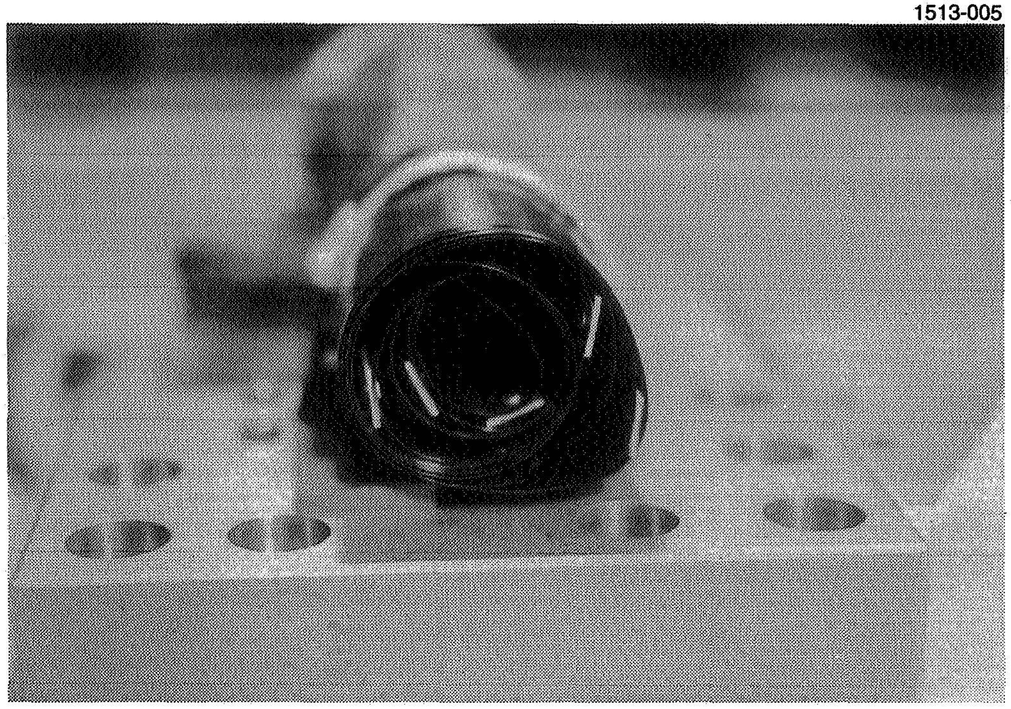

Figure 6. Development Unit Stowed Package with Wrap Discontinuities.

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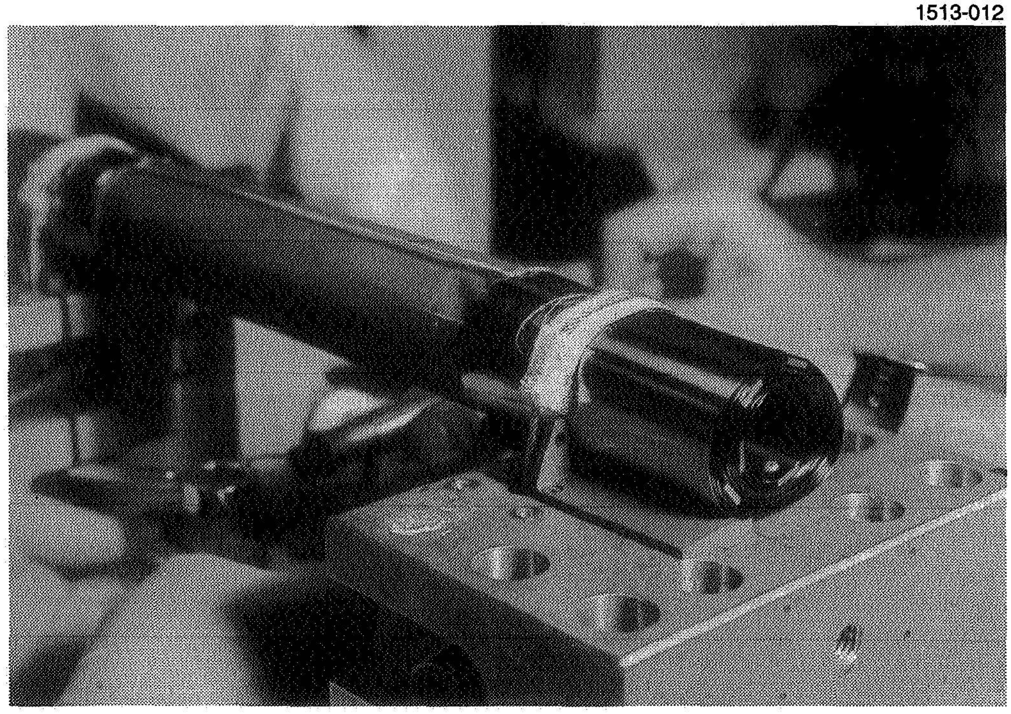

Figure 7. Development Unit Stowed Package with Uniform Nested Wrap.

To meet the stringent 66-g centrifuge loading requirement, a 1112-N (250-lb) cable preload was needed to provide sufficient preload between rolls, so that the unit would not telescope outward. The high cable preload would bring a new element into the design. When the cables were preloaded to 1112 N (250 lb), an appreciable compression of the stowed cylindrical roll was noticed. In the stowed configuration, the ramp assembly behaved as a soft spring which had been compressed with 1112 N (250 lb) of circumferential preload. Upon release of the preloaded cable, it was determined from video that the initial deployment trajectory was vertically upward to a height of approximately 25.4 to 30.5 cm (10 to 12 inches). Additional tests were performed to determine the effect of varying cable preload on the initial deployment trajectory. Test results indicated that cable preload was playing a large role in influencing the initial deployment trajectory. Video was instrumental in this program for revealing the complex deployment kinematics of the ramp assembly. The video showed that, during this initial deployment sequence, the ramp assembly was allowed to swell and unfurl before the STEM™ elements could become straightened to effectively force deployment in the desired direction. In some cases, non-compliant deployments resulted with sometimes catastrophic results, such as folding back upon itself and potentially trapping the Rover (Figure 8).

The first two development units experienced erratic deployment characteristics with sometimes unacceptable results due to the inherent complex kinematic deployment behavior. Figure 9 shows an uncontrolled and uncoordinated deployment sequence of one early development unit. The uncontrolled and uncoordinated deployment, in itself, contributed to noticeable damage to the STEM™ elements and ultimately deteriorated their lives. Acceptable deployments and initial vertical trajectory were a function of cable preload and STEM™ element damage.

<u>Controlling and Coordinating Deployment Kinematics</u>

It was evident from the number of unacceptable deployments that we were not experiencing deployment repeatability that would be necessary to satisfy program requirements. Ideal deployment kinematics of the ramp assembly would allow for the unfurling and swelling of STEM™ elements to be at a slow rate, such that they would have the opportunity to straighten at a faster rate than the unrolling process. In effect, the deployment would be controlled and coordinated. This would allow for the unit to be literally unrolled in a linear fashion from one end to the other, a characteristic which was deeply wanted by everyone involved with the program.

To promote deployment control, coordination, and reliability, thin continuous strips of Velcro™ fastener were attached to each side of the track. The continuous Velcro™ strip was sized with sufficient peel strength to reduce the unrolling rate. During deployment, this would allow the STEM™ elements to straighten immediately after being unrolled, while the remainder of the roll would remain essentially self-contained.

The addition of Velcro™ to the design provided much-needed deployment control, coordination, and damping features. The next development unit produced was outfitted with continuous Velcro™ strips. When deployed, the unit exhibited a truly perfect deployment. Video, depicting this deployment, showed that the Velcro™ attachment effectively reduced the unrolling rate and enabled a fully controlled and coordinated linear deployment. In simple descriptive terms, this deployment would be analogous to rolling out a carpet while holding the beginning end fixed. Figure 5 shows a ramp assembly deployment sequence with Velcro™ used to control deployment (note the linear deployment direction).

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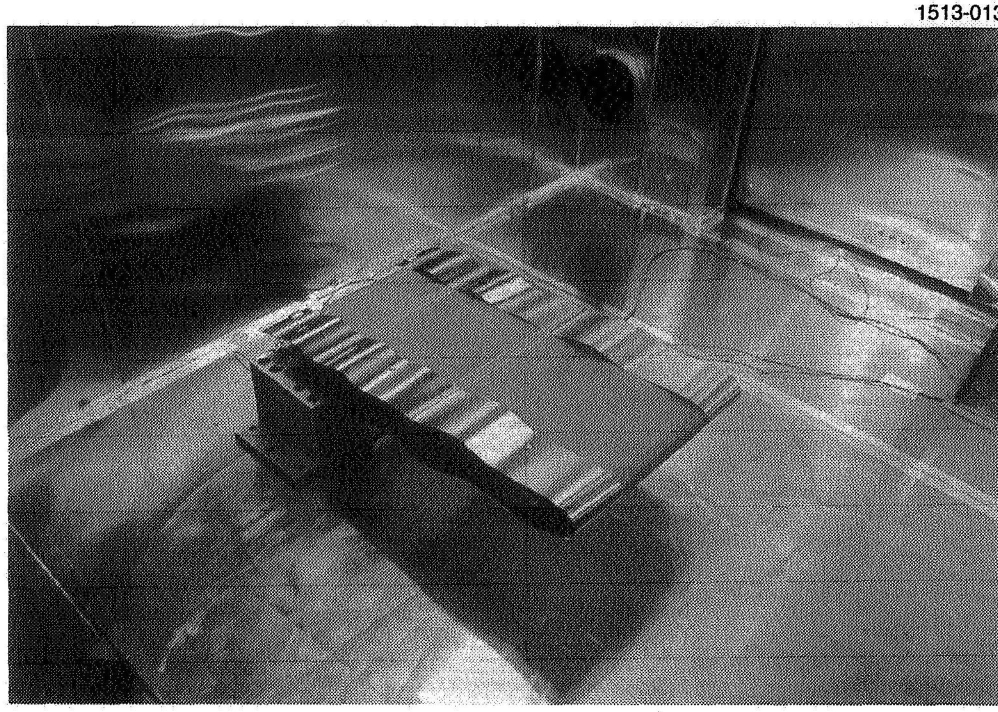

Figure 8. Unacceptable Deployment of Development Unit.

The controlled deployments that we were now experiencing led to a dramatic hardware reliability increase. The STEM™ elements were no longer being subjected to violent deployments and, as a result, were not being deteriorated. The incorporation of Velcro™ as a deployment coordination and control device allowed for one development unit to be subjected to over 40 deployment/stowage sequences with no major degradation.

Satisfying Deployment at Temperature and Inclination Extremes

Once the Velcro™ was shown to be an acceptable solution, new challenges emerged in satisfying deployment at temperature and inclination extremes. The driving requirement was to provide acceptable deployments at -140°C and at a 30° inclination at ambient conditions. Once the Velcro™ was incorporated into the design, satisfying the longitudinal 66-g centrifuge loading was no longer a problem, and the 1112-N (250-lbf) cable preload was no longer necessary. In the stowed configuration, the Velcro™ provided sufficient shear load capability between wraps, thus effectively eliminating any potential telescoping movement of the stowed package.

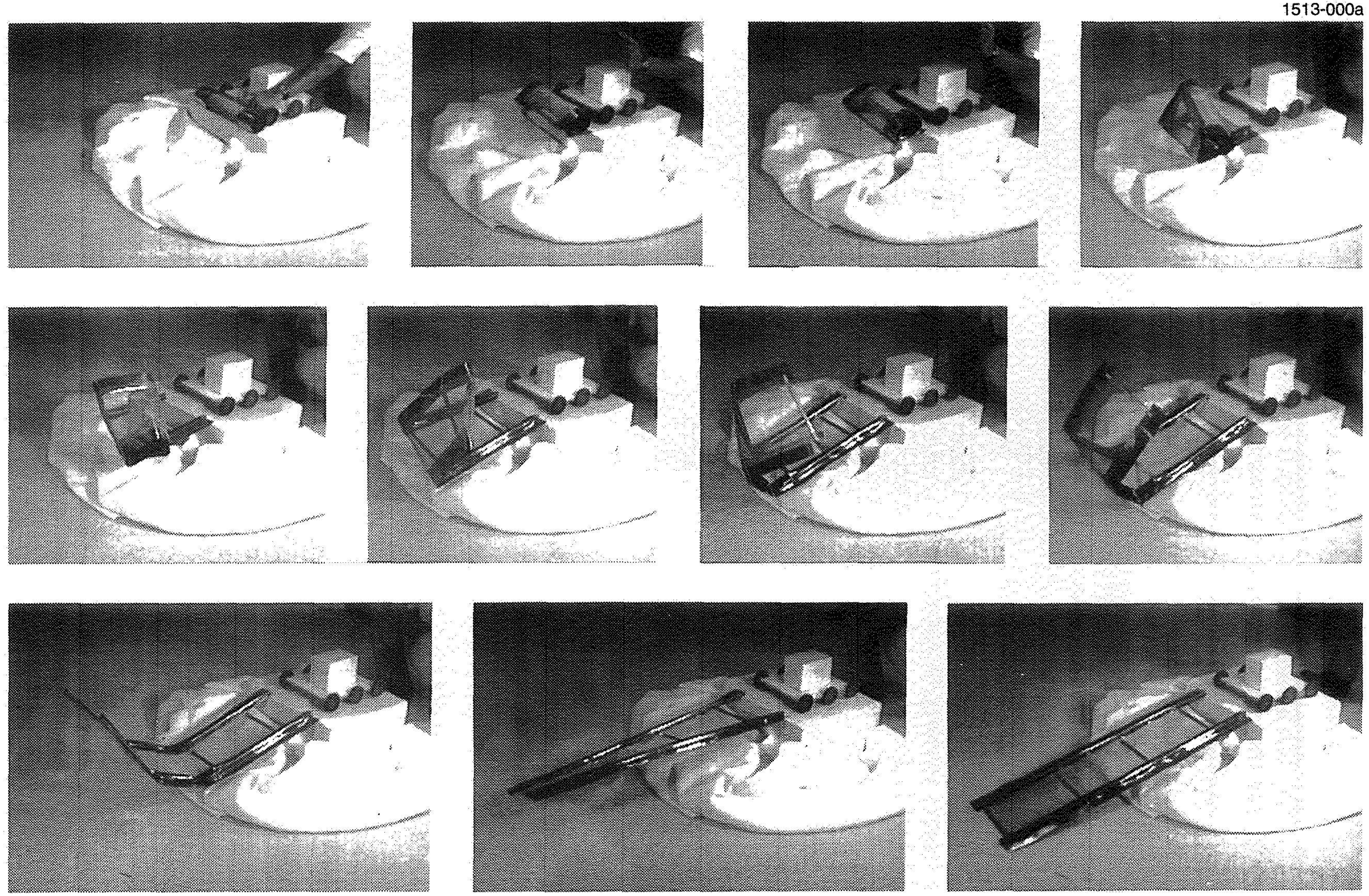

Figure 9. Uncontrolled and Uncoordinated Deployment Sequence.

The development unit, integrated with nylon Velcro™ material, underwent an entire qualification test sequence. The unit satisfied the ambient 30° inclination deployment test but failed to deploy when subjected to -140°C. During this cold test, the unit remained motionless until the temperature was elevated to approximately -40°C. It appeared that the peel strength of nylon Velcro™ was exhibiting large temperature sensitivity. The Velcro™ strip was then reduced in width to lower its peel load capability, and the two governing deployment tests were performed again. When the unit was subjected to the ambient 30° inclination test, an acceptable deployment was performed, but it was evident that the reduction in peel strength resulted in a much higher deployment speed, with signs of uncontrolled kinematics reappearing. When subjected to the -140°C deployment test, the unit again failed to deploy, even with the reduced Velcro™ width. Only until the temperature was elevated to around -40°C did the unit finally overcome the peel strength and deploy. Removal of any more Velcro™ to satisfy the cold test was simply not an option, since doing so would not satisfy the ambient 30° inclination deployment test. Rudimentary coupon tests revealed that the nylon Velcro™ material was experiencing a glass transition phenomenon which was resulting in peak peel strengths almost five times higher at low temperatures. The -40°C deployment temperature was unacceptable for the customer, since it would have imposed significant operational impacts to the mission. Because the -140°C deployment condition could not be compromised, an alternative temperature insensitive material, exhibiting similar characteristics as nylon Velcro™, needed to be found to satisfy all the deployment requirements.

Elaborate coupon testing, performed by JPL, confirmed that nylon Velcro™ was indeed experiencing a wide range of peel strengths, not only as a function of temperature, but also as functions of humidity and rate of peel. Figure 10 shows nylon Velcro™ peel strength as a function of temperature. The JPL test data showed that nylon Velcro™ would not satisfy the deployment requirements. Program efforts focused on finding an alternative fastening system, which behaved similar to nylon Velcro, but provided roughly the same peel strengths at ambient and -140°C conditions.

The JPL testing program characterized many different combinations of Velcro™ attachment types in an effort to yield a temperature-insensitive design. Test results indicated that the ideal Velcro™ attachment candidate consisted of a nylon loop with a stainless steel hook material. This combination was termed a hybrid Velcro™ which exhibited many of the desired characteristics needed. The stainless steel hooks, as opposed to nylon, allowed for a temperature-insensitive fastener. The nylon loops, as opposed to steel, provided greater attachment areas for hook engagement. Figure 11 shows hybrid Velcro™ peel strength as a function of temperature.

With full characterization complete, the hybrid Velcro™ was then integrated into the design. The development unit was then subjected again to the complete qualification test sequence. The hybrid Velcro™ performed flawlessly during qualification testing and proved to be the desired temperature-insensitive fastener.

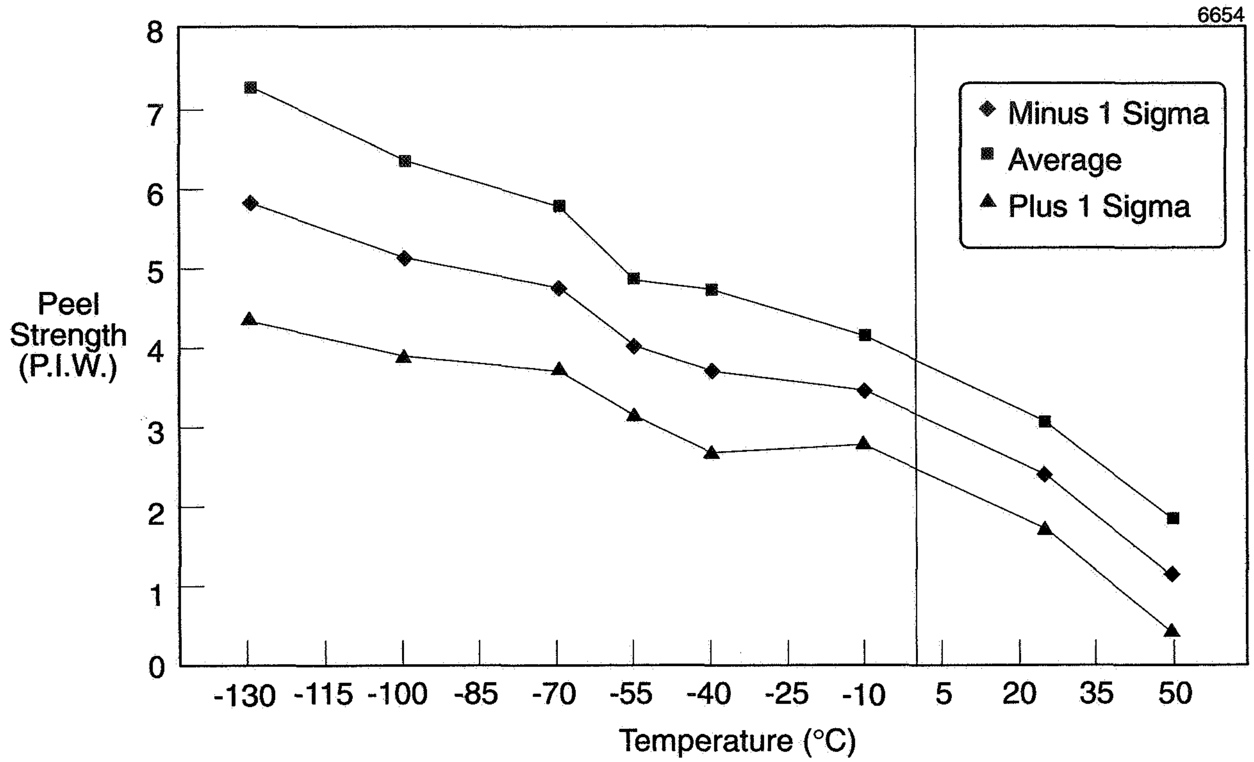

Figure 10. Nylon Velcro Peel Strength vs. Temperature.

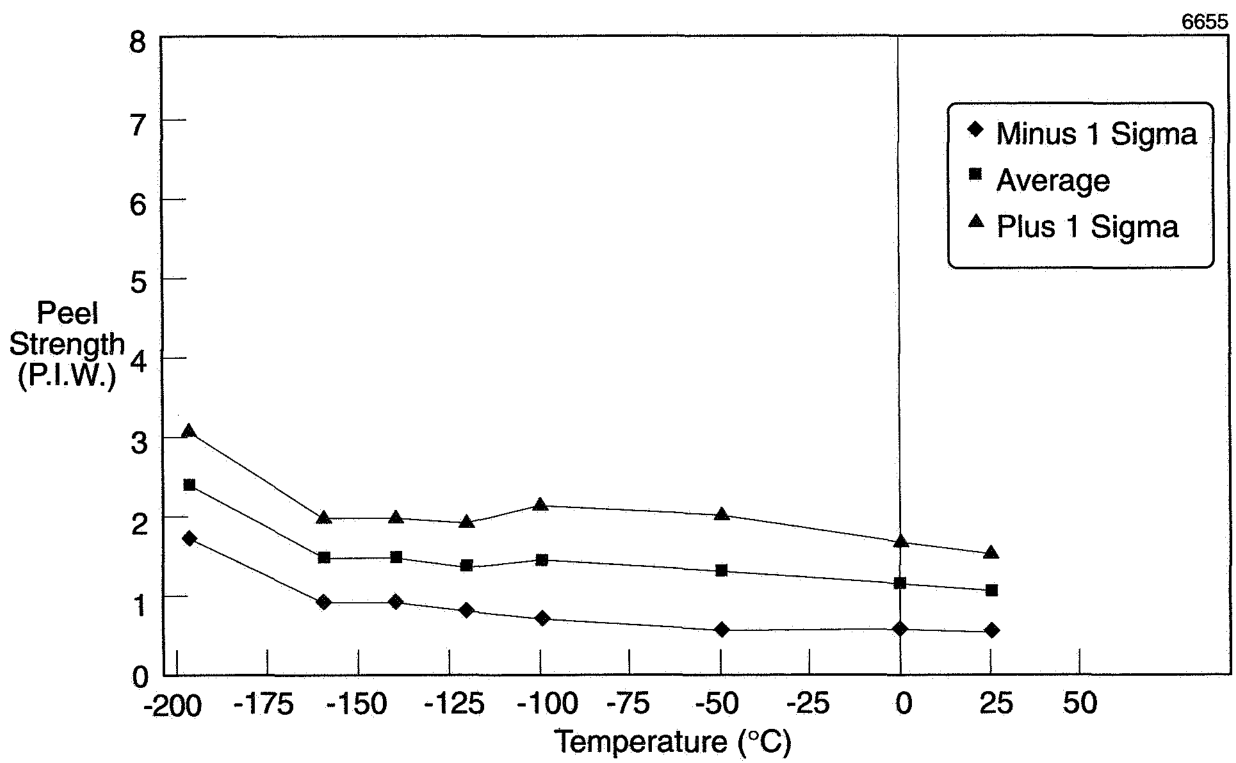

Figure 11. Hybrid Velcro Peel Strength vs. Temperature.

Flight Production Phase

Because of the many lessons learned during the program development phase, flight production and acceptance testing proceeded in a routine and uninterrupted manner. The hardware was being built, manufactured, integrated, and tested effortlessly with no anomalies. Approximately halfway through the flight hardware phase, a major concern developed, which had not been thoroughly tested. There was some uncertainty about whether the design could actually satisfy some of the buckling/deflection loading requirements necessary to support the Rover when tilted off-axis at 30°. In particular, the torsional stiffness of the ramp assembly was in question. It had never been characterized, and there was some doubt as to whether its stiffness could counteract and support an inclined Rover at a dramatic change in center of gravity. There was much speculation on what the behavior would be when the ramp was tilted ±30° off-axis while a Rover translated across it. To fully characterize the behavior, translation tests were performed with a simulated Rover vehicle. The vehicle was set up to exhibit a similar wheel base and center of gravity as the flight design. A number of off-axis translation tests were performed, all of which resulted in catastrophic results. The further the Rover translated outboard, the greater the torsional twist of the ramp became, and the more the Rover center of gravity was offset. Eventually, when the Rover reached the outermost end of the ramp, the torsional twist was so large that the Rover could not remain stable and turned over on its side. The tests revealed that even though the hardware satisfied all qualification and acceptance testing, it could not provide successful Rover egress when tilted 30° off-axis. The requirement could not be waived, and the ramp assembly behavior, when exposed to this scenario, could potentially jeopardize the entire Mars Pathfinder mission.

To eliminate this torsional stiffness problem, an integral hinge was incorporated near the root of the ramp of each STEM™ element. The hinges were designed in such a manner that the ramp would deflect in a cantilevered condition under its own weight until the outboard tip was eventually supported by contact with the ground. This feature allowed the ramp to never reach an appreciable torsional deflection during Rover egress. In effect, the Rover could never be tilted too much off-axis to over-center itself. In all translation cases, the ramp provided the Rover an ability to maintain a low center of gravity and promote stability. Subsequent testing of the integral hinges resulted in safe and successful Rover egress at all deployment conditions. The hinges were ultimately incorporated into the flight design, and all acceptance testing and program requirements were satisfied. Figure 2 shows the final flight ramp assembly configuration with integral hinges.

Conclusions and Lessons Learned

The development and qualification of the deployable ramp assemblies for the Mars Pathfinder program provided many exciting design challenges. This program represented the new "better, faster, cheaper" way that NASA is striving to do business. As with any flight program, there were many valuable lessons that were learned during this program, along with many constraints that were involved in meeting the "better, faster, cheaper" agency goals. Lessons learned during this program are summarized in the ensuing paragraphs.

1. Peel strength behavior of Velcro™-fastening systems is greatly dependent upon operating temperature, humidity, and rate of peel. Perform sufficient testing to characterize pertinent properties of Velcro™ in an effort to gain a thorough understanding of its behavior prior to implementation into a flight design. Ensure that your design can accommodate both high and low peel strength ranges, which are inherent with Velcro™-type materials.

2. Hybrid Velcro™ material, with nylon loop and stainless steel hook, is the least temperature-sensitive Velcro™ combination available. The hybrid system produces similar peel strengths over broad temperature ranges.

3. Mechanical interfaces should not be negotiated until sufficient layout work has been performed. Doing otherwise may cause unnecessary constraints during design.

4. Flat elements, which lie in contact with one another and are pinned at discrete points, need to incorporate slot features at their attachment points to allow for diametric conformance when wrapped together in a cylindrical roll.

5. Every effort should be made to document deployment testing with video to capture any complex kinematics which are not completely understood.

6. Sufficient coupon and development testing should be performed to mitigate risk prior to incorporation into design.