Verification and Validation Testing of the Bridle and Umbilical Device for Mars Science Laboratory

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Abstract—The Bridle Umbilical Device (BUD) subsystem is used during the Skycrane maneuver of the Mars Science Laboratory (MSL) during the final phases of the Entry Descent and Landing (EDL). During this phase the BUD subsystem will control the deployment of the MSL Rover from the Descent Stage. This paper covers the verification and validation testing of the subsystem. Testing included component through full system level testing. Testing ranged from simple bench top extraction tests to full system deploy drop test that included external disturbances such as the Rover mobility impulse. This paper will discuss the test that were performed, why they were performed and how these test results were used in the overall Verification and Validation of the MSL Skycrane phase.

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1. Program Background

The Mars Science Laboratory (MSL) has developed the Skycrane Landing System for its 2011 rover mission to Mars. This landing system eliminates the need for a dedicated landing structure and delivers the MSL Rover directly on the Martian surface at its fully deployed mobility wheels. This differs from previous landing architectures used by JPL/NASA’s Mars rover missions. Previous missions all had a dedicated landing system that the rover must egress from after the completion of the landing phase. After separation away from the Back-Skane (BS) and parachute, MSL utilizes an active propulsion system to control the descent of the lander portion to the surface. Like in the Mars Viking mission, MSL will use throttle-able liquid propulsion. These Mars Landing Engines (MLE) are attached to the Descent Stage (DS) which is a struturally mounted to the top of the rover at the point of separation from the BS and parachute. This configuration is known as the Powered Descent Vehicle (PDV). The PDV separates away from the BS and parachute at an altitude of roughly 1km above the Martian surface, it is at this point that the MLEs take over the controlled descent. The PDV descends to about 35m above the Martian surface, and at this point is in a targeted constant descent speed of 0.75m/sec. It is at this time that the Skycrane phase is initiated. While the MLEs provide active attitude control, the rover is released away from the DS by the firing of three pyrotechnic release nuts. Just prior to this separation, pyrotechnic cutters allow the rover to fall cleanly away from the DS by severing electrical cabling and heat rejection system tubing that exists between the separating bodies. It is at this point that the Bridle and Umbilical Device (BUD) initiates. The BUD controls the deployment of a triple bridle that is stored on DS. The ends of the triple bridles are attached to three points on the top deck of the rover. The triple bridles deploy by passing over a confluence pulley near the center-of-gravity of the DS. The bridles are wound around the bridle spool device, which unwinds per a defined profile while lowering the rover away from the DS. The Descent Brake controls this profile, which is an electro-mechanical rotational damper. Once the bridles have been fully deployed the two-body system is similar to a slung payload under a helicopter. During this deployment an umbilical is also deployed that allows communication between rover and DS during the Skycrane maneuver. The rover’s mobility system is also deployed during BUD deployment and creates a ready for touchdown mobility configuration. The DS, while maintaining the controlled descent target rate of 0.75m/s, continues descending until the rover is offloaded on the Martian surface. During this offloading the BUD system takes in any slack of the three bridles and umbilical. This is to eliminate the chance of a loose bridle entangling items on the rover top deck. Once the DS senses that the rover has been offloaded, the DS goes into a hover state and the triple bridles and umbilical are cut. Once this state is achieved the DS performs an autonomous flyaway maneuver and lands on the Martian surface 500 to 1000 meters away from the landed rover. [1]

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2. INTRODUCTION

The Mars Science Laboratory (MSL) Sky Crane Verification and Validation (V&V) program encompasses all the testing, analysis, demonstration and inspection of the various subsystems that contribute to the Sky Crane phase to show compliance to the requirements imposed on the Sky Crane phase and to increase the confidence of the success of the Sky Crane maneuver. This includes the MSL mechanical subsystems of the Descent Stage (DS), rover and rover mobility, separations and the Bridle and Umbilical Device (BUD). The MSL Sky Crane V&V program includes inputs from the various subsystem's individual V&V programs. Each subsystem’s V&V program is responsible for demonstrating the subsystem’s compliance with the requirements established for it. This demonstrates compliance all the way down to the component level of the subsystem’s design. The results of the subsystem’s V&V feed into the mechanical systems level V&V, then ultimately into the Sky Crane V&V program.

Individual subsystems V&V programs involve processes to show compliance with the requirements. Each requirement is verified and validated through analysis, inspection, test or demonstration, or a mixed combination of any of these four. For the BUD subsystem the V&V program is very heavily reliant on analysis and testing. This paper will cover the testing that was done and how this testing was coupled together with the analysis to show compliance to the requirements imposed on it. It will also show what results of the BUD V&V test program are used in the Sky Crane V&V program testing and analysis.

3. DRIVING REQUIREMENTS

In order to scope out a V&V program, one must first understand the driving requirements that were placed on the subsystem. For the BUD subsystem there were multiple requirements and the V&V program looked at which of these requirements were required to be proven by testing and analysis. The driving requirements that shaped the V&V testing program were the performance requirements placed on the BUD. In general, the driving requirements are as listed below:

(1) The BUD must fully deploy in no longer than seven seconds.

(2) The stiffness for all three briddles together, after being fully deployed, must be within a given range.

(3) The briddles and umbilical may not contact the rover top deck at any point during Sky Crane and once cut they may only re-contact the rover in designated areas. Also once cut, the severed soft-goods shall not damage the DS as they are retracted away from the rover.

Figure 1: MSL Entry Descent and Landing Sequence
Further requirements defined the electrical construction of the umbilical and dimensional construction tolerances of the bridles, but those were not driving requirements for the V&V testing program.

4. COMPONENTS OF THE BRIDLE AND UMBILICAL DEVICE

The BUD subsystem is comprised of four major components, which are called out in Figure 2. All components are mounted on the Descent Stage, except for the Bridle Exit Guides, which are mounted on the rover’s top deck. A brief description of the components and their functions are listed in the below sections.

**Figure 2: Bridle and Umbilical Device Components**

**Bridle Spool Device**

Prior to deployment into the Skycrane configuration, the bridles are stored in the bridles. The device is mounted inside the DS on one of the inner structural panels. Once the rover is released from the DS the bridles spool, which is connected to descent brake, controls the rate at which the bridles are deployed, thus controlling the rate of deployment of the rover away from the DS. The assembly consisting of the descent brake, bridles and bridge spool make up the bridge spool device assembly (see Figure 3). Prior to deployment the bridles are wound around the bridles spool. The tapered spool has deep grooves to keep each wrap of three bridles together so that they deploy together. The taper of the cone, in part, define the deployment profile. The descent brake is an electro-mechanical rotational damper. The faster the spool spins the more resisting torque the brake provides. The bridles are unwrapped from the large end to the small end of the spool, where the ends of the bridles are attached. Due to the tapered shape of the spool and the linear torque resistance with respect to rotational rate of the descent brake, the initial deployment is fastest when the moment arm is large at the large end of the spool. The deployment slows down as the spool diameter decrease and the moment arm decreases. The bridles are fabricated from a 12-strand nylon cord. The ends of the bridles contain class 1 eye splices. The DS end is spliced around a lug at the end of the bridge spool and the rover end is spliced to the bridge exit guides, which will be described in a following section. Once the touchdown signal is given, the bridge ends are cut on the rover side at the bridge exit guides. Once this happens, retraction of the bridles into the DS is done by a power spring connected to the bridge spool that gets wound up during the deployment. This power spring spins the bridge spool backwards and rewinds the cut bridles partially back onto the spool. Full retraction is not achieved, but enough retraction is done to help mitigate snagging of the free bridge ends on the rover top deck. [2]

**Figure 3: Bridle Spool Device Assembly**

**Confluence Pulley**

The confluence pulley’s main purpose is to maintain the merging point of the triple bridles to a near-single point inside the DS during the entire Skycrane phase. The bridles are routed together off of the bridge spool device, over the pulley, and then allowed to separate to go to the three points on the rover’s top deck. The maintaining of a single point of bridge confluence near the DS center of gravity is key in the Skycrane architecture, because this causes the force of the rover hanging under the DS to pull downward at this central point. This allows greater control of the guidance and navigation control though the MLE as the DS is free to pitch, roll and yaw without a resisting torque from the suspended rover. The confluence pulley is a robust tapered roller bearing pair nested inside the sheave. There is also a redundant rolling surface through simple bearings along the center shaft of the pulley. Tapered guides ensure the incoming and exiting bridles stay on the pulley sheave, even in the event of a slacked bridle situation. Figure 4 shows a picture of the flight confluence pulley prior to installation into the DS. Bridles from the bridge device assembly go into the pulley through the horn shown on the left of the figure. The bridles exit out a hole under the pulley, which cannot be seen in this figure.
Figure 4: Confluence Pulley

Bridle Exit Guides

The bridle exit guides (BEG) serve as the interface to the ends of the bridles and the rover top deck. Each BEG is equipped with a retraction drum that is powered by a pre-wound power spring. During the entire Skycrane phase, prior to rover touchdown, the bridles are fully deployed off of the retraction drum, but once slack is seen in the bridle due to the rover touchdown event, the bridles are retracted into the tower assembly around the inner drum (which is seen in Figure 5 as the inner gold colored cylindrical item). Since there is a BEG at each of the three ends of the bridles, they each can maintain the slack in each of the individual bridles. This is extremely important because the bridle spool device can only perform uniform retraction on all three bridles at once. In the event of the rover landing on an angle, or the DS translating post rover touchdown, differential slack maintenance is required by each of the bridles, and the BEG supports just that. The height of the BEG was set to keep the bridles high enough off of the rover top deck to help mitigate entanglement during the Skycrane phases. The BEG also houses the pyrotechnic cutters for the bridles and umbilical. This can be seen in Figure 5, the cutter is the silver cylindrical item near the top of the tower. This pyrotechnic cutter utilizes a piston driven guillotine cutter, which severs the bridles upon activation and severs the structural ties between the DS and rover.

Figure 5: Bridle Exit Guide (One of Three)

Umbilical Deployment Device

Digital communication and pyrotechnic firing commands are transmitted between the rover and the DS through the umbilical during the Skycrane phase. The umbilical deployment device stores this umbilical prior to the start of the Skycrane phase in a hollow two-walled cone. The top and bottom views of the flight UDD can be seen in Figure 6. Once the rover is released from the DS and the BUD deployment is initiated, the umbilical is deployed out of the umbilical can in a controlled manner. Once the last few meters are being deployed out, a retraction line attached to the umbilical is also deployed. This retraction line will serve as slack maintenance of the umbilical during the touchdown and flyaway phases of Skycrane. [3]
5. TESTING ARCHITECTURE

The Bridle and Umbilical Device V&V test program covers the tests from component level testing all the way through system testing of the device. The following sections will cover the key tests of various hardware build levels. The entire test program will not be covered as many of the lower level tests did not feed into the V&V of the Skycrane directly; however a complete list of these test is provided. The listed tests ranged from component tests to subsystem tests. These tests provided the V&V of the subsystem to ensure BUD performance in the system level tests. The V&V program was broken into three varieties of tests, (1) Component, (2) Subsystem and finally (3) System. Component tests were primarily just hardware checkouts to make sure the components functioned, such as test fits, spring torque checks, torsion shaft stiffness tests and bearing stiffness tests for example. Subsystem tests ensured that the subsystem operated as expected when all the components were combined. System level tests verified BUD performance when integrated and tested with high fidelity DS and Rover physical models, or with the flight DS and rover. Each of the following V&V tests is labeled with which level of testing was performed ((C) for component, (SS) for subsystem and (S) for system).

Each of the BUD V&V tests got a testing number designator as shown in the below list. Typically each test was referred to by the number designator, for example the full BUD deploy test was referred to as “T15”. The BUD V&V test program had two main test articles, the Engineering Model (EM) BUD and the Flight BUD. Developmental and characterization testing was done with the EM hardware. Due to the limited life of many of the components on the BUD system, the Flight BUD hardware was limited to the minimal number of tests to ensure the highest margins possible once it got to Mars. In each of the below listed test phases, the designator “EM” or “Flight” designate which model was used in each of the tests. The listing of each of the tests, T1, T2, T3, et cetera, does not define the chronological progression of the tests that were performed, they were merely numeric designations for tracking purposes.

T1 (C) Bridle Coupon Stiffness & Damping: Testing of full-length bridle samples to measure bridle performance attributes in all environments, such as temperature and vacuum. (EM)

T2 (C) Bridle Strength Degradation from Exposure: Destructive testing of bridle samples after exposure of UV and other degrading sources (EM)

T3 (C) Bridle Spool Freewheeling under spring torque: Measured the unrestrained rotational forces of the bridle spool (EM & Flight)

T4 (C) Bridle Spool Freewheeling at end of travel: Verified that the bridle termination geometry at the bridle lug was correct (EM & Flight)

T5: (C) Bridle Proof Load: Proof loading of the flight bridles to verify structural capability (EM & Flight)

T6: (C) Bridle Assy Benchtop Retraction: Demonstrated the retraction of the bridles after fully unwound off the bridle spool (EM & Flight)

T7 (C) BEG Benchtop Retraction: Demonstrated the retraction of the a bridle by the BEG once extracted fully from the BEG tower (EM & Flight)

T8 (C) Umbilical Proof Load: Verified the structural capability of the core material of the umbilical in the UDD (EM & Flight)

T9 (C) Umbilical Pyro Cut: Verified the pyrotechnic cutters capability to sever the umbilical when actuated (EM)

T10 (C) Bridle Spool Assy Drop Test w/ EMI: Verified bridle deployment profile and captured the EMI generated by the descent brake (EM)

T11 (C) Umbilical Extraction Test (cold & ambient): Verified the deployment performance of the umbilical out of the UDD in both cold and ambient conditions (EM)

T12 (C) UDD Benchtop Retraction: Verified the UDD retraction capability of the umbilical once deployed (EM & Flight)
T13 (SS) Umbilical-Rover Recontact: Simulation validation testing of the bridles and umbilical dynamics post cutting to demonstrate no recontact will occur (EM)

T14 (S) Vibe/Acoustic/Pyro: System level environmental vibration, acoustic and pyrotechnic shock testing (Flight)

T15a (SS) Full BUD Deploy: Full system deployment test to verify deployment dynamics of all components (EM & Flight)

T15b (SS) BUD Full System Deploy in Ambient with Mobility Impulse: Full system deployment test to verify deployment dynamics of all components with a representative rover mobility impulse during deployment (EM)

T16 (SS) Full BUD Retract: Post T15, verification of retraction of bridles and umbilical after a full system deployment (EM & Flight)

T17 (SS) Thermal Full BUD Deploy: Verification of a full-system deployment while under thermal-vacuum conditions (EM)

T18 (SS) Thermal Full BUD Retract: Verification that bridles and umbilical will retract under thermal-vacuum conditions (EM)

T19 (C) Thermal Pulley Torque Characterization: Verification of the confluence pulley performance under all thermal-vacuum environments (EM & Flight)

T20 (C) UDD Torque Characterization: Measurement test of the UDD’s umbilical retraction device (EM & Flight)

T21 (S) Drop Test of Bridle and Umbilical Device System Test without UDD (Optional): Verification of bridle device and pulley performance on the flight unit (This was combined into T22 and not performed without the UDD)

T22 (S) Drop Test of Bridle and Umbilical Device System Test (Optional): Verification of the BUD performance with the flight or flight fidelity DS and rover (EM)

T23 (S) Slow Walkout Full BUD Deploy: Post spacecraft environmental testing, demonstrate full deployment via a slow/unloaded walkout of the BUD bridles and umbilical (Flight)

T24 (S) Slow Walkout Full BUD Retract: Post spacecraft environmental testing and T23, demonstrate retraction after walkout deployment of the bridles and umbilical (Flight)

T25 (C) Umbilical Heat Set Test: Verify that no permanent set occurs to the umbilical when accelerated aging is applied to the umbilical in a stowed configuration. (EM)

T26 (S) Bridle Device Pyroshock: Verify functional performance post exposure to pyrotechnic shock environments (EM & Flight)

T27 Retraction Line Proof load: Structural verification of the retraction line in the UDD (EM & Flight)

T28 (C) Umbilical Retraction Dynamic Shock: Verification that the pyrotechnic shock produced by the umbilical cutting does not degrade retraction performance (EM)

T29 (C) Umbilical Retraction Line Margin Testing: Destructive testing of the UDD retraction line to establish line load capabilities (EM)

T30 (C) Descent Brake Testing: V&V component level testing of the descent brake to verify functional performance and qualification testing of the unit. (EM & Flight)

Each level of testing was used to verify that the hardware performed as expected and to capture dynamic characteristics of the hardware to aid in analytical model correlation. Analytical models were generated long before hardware was ready for testing. These models aided in determining the dynamic performance characteristic that the hardware needed to be design to. For example prior to determining the shape of the bridle spool, analytical models were built and looked at what deployment profiles could be achieved with different shapes. Early on tests were done to make sure these models were correct. Once the analytical models captured the basic Skycrane architecture, refinements to the model were done as additional knowledge from testing and design matured. Many of these refinements came from the V&V tests. These refinements were as simple as adjusting the coefficient of drag in a confluence pulley to as complex as stiffness of the bridles per a deployed length at a given temperature and for a certain geometry.

### 6. Component Level Testing

Component level testing was done on the various BUD components before it was integrated into subsystem level tests. This testing was the backbone on which dynamic performance parameters were built on. Performance parameters captured in component level testing were integrated into the analytical models at the lowest level. The following subsections list some of the key component level V&V test and how they fed into the BUD V&V.

#### Descent Brake [T30]

Component level testing of the descent brake was one of the most important components to test at this level. The descent brake provides the primary drag source to limit the rate of deployment of the rover. This electro-mechanical rotational damper provides a resisting torque that is proportionate to the rotational rate of the input shaft. Testing was done by performing short runs of trapezoidal speed-time profiles. Because of the rotational inertia of the descent brake, testing at a constant speed was necessary to eliminate inertial forces due to angular acceleration. The plot below shows an example of a loading profile that was used in testing the brake.
Figure 7: Descent Brake Test Profile

The test configuration was a straightforward design. It included a drive motor that was connected to a rotating torque sensor that then was connected to the descent brake input shaft. By controlling the drive motor, the desired speed profiles were achieved. Testing was done not only at ambient temperatures but also at the hot and cold flight qualifications temperature and under Martian atmospheric environments. Analytical models of the initial performance were performed and fed into the subsystem level analytical models. These rotational inertial values were validated in future subsystem tests.

Bridles [T1]

The Skycrane maneuver involves an actively controlled DS, therefore, a requirement was generated on the stiffness of the deployed bridles. Too stiff of a bridle and the DS guidance controller would go unstable and too soft of a bridle caused a lack of ability to control the slung rover. Testing of the bridles was done by taking a known mass and suspending it with a full length of bridle material. An inline load cell was placed between the bridle and mass and the system was suspended from an extremely stiff structure. The system was then excited inline with the bridle and the frequency and damping could be obtained by looking at the load data verses time. Knowing the mass and frequency, a stiffness could be calculated. Temperature is the largest factor in variation of the stiffness of the bridle: the colder the material, the stiffer it gets. There is a large temperature range on the bridles when it is used in the Skycrane phase, so testing to capture the stiffness dependency on temperature was required to verify that the stiffness requirement could be met. In order to test the bridles at cold temperature, the material had to be baked out under vacuum to get all moisture out. The bridles were then dynamically tested in a vacuum chamber under a simulated Martian atmosphere. The temperature was varied and stiffness versus temperature relationships could be calculated. Figure 8 shows a picture of the bridles inside the thermal-vacuum chamber during this testing. The bridles are shown as the thin lines running up the chamber connecting to the upper triangular structure. The upper structure was rigidly mounted to the top of the chamber and lower ends of the bridles were attached to suspended weights. Once the correct environmental conditions were met, the suspended weights were dropped and the bridles snatched the falling weights. The dynamics response of the bridles bouncing the weights was recorded and dynamic performance of the bridles at various environmental conditions was calculated.

Figure 8: Bridle Testing Under Thermal-Vacuum Conditions

Bench-Top Retraction Tests [T6, T7 and T12]

Retraction tests were done on all retracting hardware. Initial tests were done at the bench-top level. These tests were done to demonstrate the performance of the devices. The use of a string-encoder (linear displacement measurement transducer) and a loadcell was all that was required. This provided displacement and load information of the retraction device as retraction in and out of the device was performed. This was compared to the expected values to verify that the retraction force and distance was adequate for meeting the requirements. While this was not an actual verification, as it did not have proper geometry and initial conditions, it did verify that the device was operating as expected.

Bridle Device Assembly Full Deploy Test [T10]

This was the first full deployment of the bridle device assembly. This test demonstrated the performance of the descent brake and bridle spool device working together to control the deployment of a mass.
Due to the difference in gravity of Mars as compared to Earth, a Mars weight rover mass was used, which is about 3/8 of the actual mass of the rover. The test configuration took the bridle device and mounted it on the floor under a bridge crane. A line was run from the bridle device up to a spreader bar mounted to the over-head crane then to the hung mass. A release line was connected to the end of the deployment line and was anchored right next to the bridle device by a mechanical release. The bridles were then attached to the deployment line. The test was conducted by deploying the mechanical release, which released the release line and transferred the hung load in the deployment line onto the bridles, which in return initiated the bridle device deployment. The deployment ended with the snatch of bridles at the end of the spool. The drop mass’s initial height was high enough that it did not ever touch the ground during the deployment so some snatch dynamics could be looked at.

![Figure 9: T10 Test Configuration](image)

Key instrumentation included a rotary encoder mounted on the end of the bridle spool to capture spool rotation, an inline string-encoder to capture bridle payout length and an inline loadcell at the end of the bridle to capture pullout force. Other instrumentation included diagnostic readings from the descent brake including temperature and resister bank current levels. There were also accelerometers on the spreader bar to help capture test-induced dynamics. Results from this test series aided in validation of the performance of the bridle device assembly. The analytical models already had a test verified descent brake model; now the addition of the bridle spool and bridles could be verified. The most significant results from this test series were a better understanding of how the bridles influenced the deployment profile. The point at which the bridles exited the bridle spool generates the instantaneous moment arm for calculating the torque applied to the bridle device when multiplied by the force from the inline loadcell. The bridle spool’s drum radius can be calculated from the amount of rotation seen in the spool’s encoder, but what was not known is the additional amount of moment arm due to the thickness of the cordage. Taking the bridle spool radius plus half the diameter of the cordage coming off approximated the actual moment arm. Also from this test series, an understanding of the amount of drag associated with the bearings in the bridle spool device was calculated. Having the known drag data from the descent brake, any additional drag seen could be attributed to the bridle spool bearing and friction of the bridles coming off of the spool.

It was found that this was very small and on the order of only a few percent of the overall drag generated from the descent brake. Also included in this test was EMI measurement devices to capture the magnitude of EM field generation. It was found that an insignificant amount of EM fields were generated during the deployment process.

7. SUBSYSTEM LEVEL TESTING

Subsystem level testing involved taking all of the BUD components and combining them into a test series. These tests verified that the component’s performance when combined performed as expected as a subsystem. Dynamics of the tests were captured through the use of instrumentation to aid in the validation of the analytical models. Analytical models of the test configurations were built and the test results fed into these models. Parameters were updated based on the test dynamics seen. The parameters adjusted were only those only that had not been characterized in component level tests. For example, the drag parameters of the descent brake were not adjusted as these values had been characterized in the component level testing of that item; however, the drag associated with bridles dragging off of the bridle spool in this new flight like configuration could be adjusted based on the values seen in the tests.

BUD Full System Deploy in Ambient [T15a and T16]

The first subsystem level test was a full deployment of the system in ambient conditions. Testing initially was done with only the EM hardware. Since the DS and rover were not available and could not be tied up while the BUD tests were being done, simulators of the DS and rover were designed and built. These simulators had the correct interfacing geometries so that the BUD hardware was mounted with the correct orientations with respect to each other. These test fixtures were also designed to support all
of the tests support equipment like high-speed cameras, data acquisition and lifting points.

The test involved mounting all the BUD hardware on the DS and rover simulator. This created a Powered Descent Vehicle (PDV) configuration, which was hoisted to the ceiling using an overhead crane. The test was conducted by releasing the rover simulator from the crane supported DS simulator, which initiated the mocked-up Skycrane phase by deploying the rover away from the DS. The entire BUD system would deploy, including the umbilical deployment device. Deployment ended with the snatch of the rover simulator on the fully deployed bridles. Once the BUD was fully deployed, the crane was lowered to offload the bridles and the demonstration of the bridle and umbilical retraction could be done.

The DS simulator was built to support all BUD hardware other than the rover mounted BEGs.

![Figure 10: Descent Stage Simulator](image)

The simulator was built up using a simple square tube frame. A mounting plate (shown as purple in the figure) was designed with the same interface tolerances as the DS hex panel that the BUD hardware ultimately mounts to for flight. On this panel the bridle spool device and umbilical deployment device are mounted. The frame had three lift points to allow the assembly when fully configured to be lifted to the ceiling.

The rover simulator, or known as the BUD Drop Item (BUDDI) was designed to hold the bridle exit guides at the proper location as seen on the rover.

![Figure 11: Rover Simulator](image)

Instrumented BEG mounting plates were attached at the three corners of the inner triangular plate. A simple kinematics mount was built so that vertical and shear loads seen by the BEG could be captured. This was the method used to measure the individual bridle loads.

![Figure 12: Instrumented BEG Mount to Capture Bridle Loads](image)

The use of a six-degree-of-freedom force-torque sensor was statically mounted to the BUDDI in the area where the umbilical end is mounted to the top deck of the rover. This sensor recorded the forces of the umbilical on the rover during deployment.

The BUDDI had a center swivel-D ring that was used to preload it up against the DS simulator prior to deployment. This connection, when commanded, was released, which initiates the deployment of the BUD. On the four legs of the BUDDI were configurable weight stacks. Increasing the number of these ¼” thick steel plates until the desired weight was achieved gave flexibility to quickly adjust the drop mass as well as aid in getting the center of gravity in the middle.

Once the DS simulator and the BUDDI was built up to the correct configuration and balanced, the two were mounted together to create the simulated PDV configuration. At this
point all the BUD hardware was mounted as well as all the instrumentation.

**Figure 13: T15a Test Configuration Prior to Test**

The above figure shows the fully configured test setup just prior to lifting the assembly for testing. This assembly was then hoisted and the test was performed. Figure 14 shows the test configuration about one second after the release of the BUDDI from the DS simulator. In this figure it can be seen that the bridles only support the BUDDI and that all other structural ties to the DS have been released. The deployment of the bridles controlled the rate at which the BUDDI descended.

**Figure 14: T15 Test Underway**

The use of high-speed cameras mounted on the DS simulator captured the deployment of the bridles off of the bridle spool and verified that proper routing was done over the confluence pulley. A second DS mounted high-speed video camera viewed the deployment of the umbilical.

After full deployment of the BUD was done, the test article was in the Sky-crane configuration. Lowering the crane allow demonstration of the retraction of the bridles and umbilical once the BUDDI was set down on the floor. The use of blocks under the legs of the BUDDI set the simulated rover top deck at expected worst-case touchdown angles.
Then slewing the crane to the side simulated the DS drifting horizontally. The figure below shows this configuration.

A total of three full weight deployments were done in this test series. Deployment profiles of each test were seen to be less than one percent off from each other. This provided confidence on the repeatability of the performance of the hardware.

Once the flight hardware was fabricated, a single test was performed using the same test fixtures. Performance of the flight hardware was compared to that of the EM hardware. The flight descent brake had a different rotational damping coefficient so the profiles were different. After adjusting this single parameter in the EM correlated analytical model, only a fraction of a second deviation between the test data and the analytical prediction was seen on overall deployment time. The bridle spool bearing drag was adjusted slightly and the test data and analytical models correlated to within a few percent of one another. The figure below shows the simulation results before and after the parameter change in comparison to the test results.

Once the flight hardware was fabricated, a single test was performed using the same test fixtures. Performance of the flight hardware was compared to that of the EM hardware. The flight descent brake had a different rotational damping coefficient so the profiles were different. After adjusting this single parameter in the EM correlated analytical model, only a fraction of a second deviation between the test data and the analytical prediction was seen on overall deployment time. The bridle spool bearing drag was adjusted slightly and the test data and analytical models correlated to within a few percent of one another. The figure below shows the simulation results before and after the parameter change in comparison to the test results.

This test also demonstrated other parameters such as deployed bridle stiffness, damping at full deployment and forces of the umbilical imparted on the rover during deployment.

**BUD Full System Deploy in Ambient with Mobility Impulse [T15b]**

During the deployment of the BUD subsystem, the rover’s mobility is deployed. The deployment and latch-up of the front and rear mobility rockers are done before the BUD briddles snatch the rover at the end of BUD deployment. The mobility deployment occurs about 1/3 of the way into the BUD deployment causing a loading impulse into the entire BUD subsystem. Analytical models capture the mobility impulse and its effect on the BUD hardware. Margins on all of the BUD hardware were shown to be positive by the analytical models. What was not captured in the model is any unknown secondary responses of the BUD system and how they may affect the Skycrane. This test series would demonstrate BUD behavior when subjected to a mobility impulse and verify that no secondary dynamics resulting from this impulse would impact BUD performance.

There was not a rover available for testing, and even if there was the predicted loads could not be generated because of the constraints of an Earth bound test. If the full mass mobility were deployed here on Earth, the loads would be too high on the BUD and rover. This is due to the increased deployment speed due to the increased gravity seen on Earth as compared to Mars. If mass was taken out of the mobility to get to loads low enough then the impulse seen by the BUD would be lower than the current analytical model predictions. Therefore, a Mobility Impulse Simulator (MobIS) was designed. The design requirement for MobIS was to impart an impulse into the BUD hardware when the descent brake reached the rotational speed that was the same as the predicted speed seen in the simulations. The impulse shall also generate a rotational velocity increase in the brake.
to the same level as seen in the simulations, thus causing similar input torque levels as seen in the analytical model. Due to the differences in BUD deployment profiles on Earth with a 3/8 mass drop item, timing and impulse levels had to be analyzed to meet these requirements. In addition the load levels of all of the other BUD hardware could not be exceeded past the current worst case levels as predicted by the Skycrane analytical model.

The MobIS design involved taking some of the mass from the BUDDI and mounting it on a linear slide. The mass initially was held at the top of the slide and when commanded was released and allowed to slide downward until it impacted honeycomb attenuators. The release of the mass temporarily offloads the bridles; this is similar to when the mobility is released. The impact and attenuation at the end of the slide simulated the impact and latching of the mobility’s forward and rear rockers.

MobIS was then mounted on the bottom of the BUDDI after the removal of the outrigger legs.

Analysis of the MobIS impulse was done to determine what the correct ratio of static versus deployable mass was required to generate the correct impulse. Because the BUDDI’s mass is only 3/8 the mass of actual rover, the ratio of deployed to static mass was greater in comparison to the rover’s mass ratio of mobility to chassis mass.

Figure 17: Mobility Impulse Simulator (MobIS)

Figure 17 shows the sequence of the MobIS deployment while the BUD deploys. The MobIS top deck had the BEG rover interfaces and allowed the BEG to be mounted just as they were in the BUDDI. The first frame shows the three BEGs and the bridles going upward out of them toward the DS simulator. The second frame shows the release of the drop mass as it slides down the vertical slide. The third frame shows the impact of the sliding mass into the attenuators at the end of the slide, and finally the fourth frame show the bridles stretching as the impact load is transferred into bridle load and ultimately torque in the bridle spool and descent brake.

Only one test was performed with the full level impulse. The BUD deployed as expected and there were no unusual behaviors seen in the bridles. Because there were no anomalies seen, the rest of the planned deployments with MobIS were canceled.

BUD Full System Deploy in at Temperature [T17]

All of the BUD components had been Qualified through their entire temperature range through component level thermal tests. However to demonstrate that the BUD subsystem performs as expected at reduced temperature a full subsystem deployment in a thermal-vacuum chamber was scoped. This test involved taking the same setup as seen in T15b but removing MobIS. Due to the size.
restrictions of the thermal-vacuum chamber the outrigger legs of BUDDI as seen in T15a could not be attached. Figure 19 shows the test configuration inside of the thermal-vacuum chamber. The same test chamber as was used in the full-length thermal-vacuum bridle component test as was used for the T17 test. The DS simulator was rigidly mounted to the top of the chamber and the rover simulator (modified BUDDI, without legs) was released and the BUD was allowed to deploy the rover simulator.

Figure 19: T17 Test Configuration

Since all of the BUD hardware had already been qualified at temperature, this test was not a qualification test, therefore the temperature of the test was performed at the minimal flight allowable temperature and not the minimal qualification temperature.

In order to achieve the desired temperature cold plates and shrouds were attached to the DS simulator. This was done instead of cooling the entire thermal-vacuum chamber, which would have taken longer to achieve the desired temperature as well as cost more. Multi-layer insulation (MLI) was wrapped around the shrouds to create thermal containment. Figure 20 shows the DS simulator and modified BUDDI assembly as it was being lifted into the thermal-vacuum chamber. Once lifted to the top, the DS simulator was mounted to the top of the chamber and the thermal shrouds and MLI was wrapped around the test article. The chamber was then pumped down to vacate all moisture in the system. It was then backfilled with a simulated Martian atmosphere and then taken to the desired test temperature. Once both temperature and pressure was met, the modified BUDDI was release and the system deployed. This test produced no anomalies. The predicted performance of the BUD sub-system under vacuum and temperature was as expected when compared to the already at-temperature component-validated simulation model.

8. SYSTEM LEVEL TESTING

Slow Walkout Full BUD Deploy [T23]

The flight BUD system was delivered to the MSL flight vehicle prior to spacecraft level environmental testing. After spacecraft environmental testing, each subsystem of the spacecraft was de-mated. During the de-mating of the DS from the rover, the BUD demonstrated a walkout of the deployment hardware. This was accomplished by placing the mated DS and rover on a cart, and then using an overhead crane, the DS was raised up and away from the rover. This was done at very low crane speeds. Inspections of all the BUD deployables were inspected as the lift occurred. Before and after configurations of the flight vehicle during the BUD walkout test are shown in Figure 21 and Figure 22. It can be seen in Figure 22 that the DS has been lifted and translated to the right and the BUD bridles and umbilical are still under tension as the retraction mechanism in the BUD keeps the lines from slacking.
The final system level test that was performed on the BUD was the T22 test. This test was combined with rover mobility and EDL separations V&V testing. The combined test was called the Skycrane Full Motion Drop Test (SFMDT). This test involved the developmental test model (DTM) DS and rover. These DTM vehicles were both high-fidelity models that were structurally representative of the flight vehicle in all of the interfaces with the BUD, both on the DS and the rover. Figure 23 shows the test article prior to the test. When compared to Figure 21, which is of the flight vehicle, it can be seen that both vehicles looked similar. In the SFMDT, the rover was offloaded to ~3/8 mass of the flight rover. This was to keep the loads representative to the Mars flight loads here on Earth. In addition to lightening the rover chassis, the rover’s mobility was also lightened by the removal of the wheels and drive actuators. This allowed both the BUD and rover mobility to be deployed in Earth gravity while maintaining positive structural margins during deployment.

The test article was raised to the top of the test facility using the overhead crane. Once the item was at the top and secured, the rover was released from the DS and the BUD was allowed to deploy the rover. This was the highest fidelity deployment of the BUD. Figure 24 shows the sequence of event during the BUD deployment. In frame one, the DS and Rover are at the top of the test facility. In frame two, the rover has been released and is being deployed by the BUD. In frame three, the BUD has deployed the rover further and the mobility on the rover is also in the process of deploying. In the final frame, frame four, it can be seen that the BUD has fully deployed the rover and the rover’s mobility is also full deployed. This is the configuration that the spacecraft will be in just prior to the rover touching down.
9. CONCLUSION

The Mars Science Laboratory (MSL) Skycrane Verification and Validation (V&V) program encompassed all the testing, analysis, demonstration and inspection of the various subsystems that contribute to the Skycrane phase to show compliance to the requirements imposed on the Skycrane phase and to increase the confidence of the success of the Skycrane maneuver. This includes the MSL mechanical subsystems of the Descent Stage (DS), rover and rover mobility, separations and the Bridle and Umbilical Device (BUD).

The BUD V&V program was heavily reliant on analysis and testing in order to demonstrate satisfaction of the BUD requirements. As discussed, the testing was coupled together with the analysis to show compliance to the requirements imposed on it. Testing of the BUD ranged from component level tests as simple as bench-top retraction tests, to high fidelity system level testing that included both the flight DS and rover. The test-centric BUD V&V program fed the validation of the MSL BUD analytical model. BUD performance and characterization was driven by these test verifications. It was this combination of verification and validation that shaped the BUV V&V program as presented.

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REFERENCES


**BIOGRAPHY**

*John Gallon* received his BS in Mechanical Engineering in 2000 from the University of Kansas. After graduation he worked 5 years with the Department of Defense at the Naval Air Warfare Center Weapons Division at China Lake, CA. Mr. Gallon started to work for JPL/NASA in 2005 and currently works on the Cruise, Entry, Descent and Landing Team and is the Separations and Bridle Umbilical Device Cognizant Engineer for the Mars Science Laboratory.