Project Morpheus:
Morpheus 1.5A Lander Failure Investigation Results

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ABSTRACT

On August 9, 2012 the Morpheus 1.5A vehicle crashed shortly after lift off from the Kennedy Space Center. The loss was limited to the vehicle itself which was pre-declared to be a test failure and not a mishap. The Morpheus project is demonstrating advanced technologies for in space and planetary surface vehicles including: autonomous flight control, landing site hazard identification and safe site selection, relative surface and hazard navigation, precision landing, modular reusable flight software, and high performance, non-toxic, cryogenic liquid Oxygen and liquid Methane integrated main engine and attitude control propulsion system. A comprehensive failure investigation isolated the fault to the Inertial Measurement Unit (IMU) data path to the flight computer. Several improvements have been identified and implemented for the 1.5B and 1.5C vehicles.

1. INTRODUCTION

NASA's strategic goal of extending human activities across the solar system requires an integrated architecture to conduct human space exploration missions beyond low earth orbit (LEO). This architecture must include advanced, robust in-space transit and landing vehicles capable of supporting a variety of lunar, asteroid and planetary missions; automated hazard detection and avoidance technologies that reduce risk to crews, landers and precursor robotic payloads; and in-situ resource utilization (ISRU) to support crews during extended stays on extraterrestrial surfaces and provide for their safe return to earth. The Advanced Exploration Systems (AES) Program portfolio within NASA includes several fast-paced, milestone-driven projects that are developing these necessary capabilities and, when integrated with subsystem technologies developed by Science Mission Directorate (SMD) investments, can form the basis for a lander development project. Specifically, the Morpheus, Autonomous Landing & Hazard Avoidance Technology (ALHAT), and Regolith & Environment Science & Oxygen & Lunar Volatiles Extraction (RESOLVE) projects provide the technological foundation for lunar surface demonstration missions later in this decade, and for key components of the greater exploration architecture required to move humans beyond LEO.

The Morpheus Project provides an integrated vertical test bed (VTB) platform for advancing multiple subsystem technologies. While technologies offer promise, capabilities offer potential solutions for future human exploration beyond LEO. Morpheus provides a bridge for evolving these technologies into capable systems that can be demonstrated and tested. This paper describes the activities of the Morpheus Project, ongoing integration with ALHAT through FY12-13, and expectations for the future, with the goal of developing and demonstrating these human

Figure 1 - Morpheus 'Alpha' Vehicle is prepared for testing at Kennedy Space Center in August 2012.

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spaceflight capabilities with robotic missions to the lunar surface.

The Morpheus Project provides a liquid oxygen (LOX) / liquid methane (LCH4) propelled vehicle that, when leveraging subsystem designs developed by other VTBs such as the Marshall Space Flight Center's (MSFC) Mighty Eagle Lander, may be developed into reusable platforms for in-space transit and/or planetary landing for multiple missions and payload capacities. Such platforms could directly support robotic missions and would eventually mature into capabilities advantageous for manned missions.

The LOX/methane propulsion system is one of two key technologies that Morpheus is designed to integrate and demonstrate. The Morpheus LOX/methane propulsion system can provide a specific impulse during space flight of up to 321 seconds; it is clean-burning, non-toxic, and cryogenic, but space-storable. Additionally, for future space missions the lox and/or methane could be produced in situ on planetary surfaces, and the oxygen is compatible on-board with life support systems and power generation. These attributes make LOX/methane an attractive propulsion technology for a lander of this scale.

ALHAT, the primary Morpheus payload, provides the second key technology: autonomous landing and hazard avoidance. When landing autonomously on any planetary or other surface, the vehicle must be able to identify a safe landing site that is free of large boulders, rocks, craters, or highly sloping surfaces. Morpheus is designed to carry ALHAT sensors and software supporting tests that will demonstrate an integrated vehicle capability to perform these tasks.

2. SYSTEM DESCRIPTION

The VTB system elements include the flight test vehicle, ground systems, and operations.

A. Vehicle

Morpheus design and development began in June 2010, primarily by an in-house team at NASA's Johnson Space Center. The current iteration is the Morpheus '1.5 Bravo' vehicle, and system description references the current vehicle build.

Morpheus is a "quad" lander design with four tanks and a single engine. The primary structure consists of welded aluminum box beams, machined parts, and aluminum plate. The landing struts have honeycomb crush pads in the feet to attenuate landing loads. The propellant tanks are made of welded aluminum hemispheres. The avionics and GN&C components are located on a plate that spans the top deck of the primary structure.

The propulsion system uses an impinging element-type engine design, with liquid oxygen and methane as the propellants. The engine is film-cooled and operates as a blow-down system producing up to 5000 lbf of thrust. Two orthogonal electromechanical actuators (EMAs) gimbal the engine to provide thrust vector control of lateral translation and pitch and yaw attitudes. LOX/LCH4 pencil thrusters fed from the same propellant tanks provide roll control with a redundant set of helium jets that use the pressurized helium in the propellant tanks onboard as a backup system. Varying the engine throttle setting provides vertical control of ascent and descent rates.

The avionics and power subsystems include the flight computer, data recording, instrumentation, communications, cameras, and batteries. The flight computer is an AITech S900 CompactPCI board with a PowerPC 750 processor. Up to 16 GB of data can be stored on board. Data buses include RS-232, RS-422, Ethernet, and MIL-STD-1553. Multiple channels of analog and digital inputs are used for both operational and developmental flight instrumentation, including temperature sensors, pressure transducers, tri-axial accelerometers, and strain gauges. Wireless communications between ground operators and the vehicle use a spread spectrum frequency band. Two on-board cameras provide views of the engine firing during testing. Eight lithium polymer batteries provide vehicle power.

The GN&C sensor suite includes a Javad Global Positioning System (GPS) receiver, an International Space Station (ISS) version of Honeywell's Space Integrated GPS/INS (SIGI), a Systron Donner SDI500 Inertial Measurement Unit (IMU), and an Acuity laser altimeter. The vehicle is able to determine position to less than one meter, velocity to less than three cm/second, and attitude knowledge within 0.05 degrees.

The vehicle software is architected around Goddard Space Flight Center's (GSFC) Core Flight Software (CFS). GSFC designed CFS as a set of reusable software modules in a flexible framework that can be adapted to various space applications. Morpheus software developers built upon CFS by adding custom application code unique to the Morpheus vehicle and mission design.

The initial Morpheus VTB 1.0 configuration was tested from April 2011 through August 2011. In late 2011 and early 2012, the team began upgrading the VTB to the Morpheus 1.5 configuration, including sequentially higher performance HD4 and HD5 engines, an improved avionics and power distribution design, the addition of LOX/methane thrusters for roll control, and the incorporation of the ALHAT sensors and software. In August 2012, the original vehicle was lost in a test crash. The vehicle was rebuilt with over 70 upgrades and is designated as the

Morpheus 1.5 ‘Bravo’ vehicle. This vehicle configuration is currently in testing as described in later sections. A ‘Charlie’ vehicle is also under construction.

B. Ground Systems

The VTB flight complex (VFC) includes 20’ x 20’ concrete pads located on a section of the JSC antenna range near an old Apollo-era antenna tower. About 2000 feet away is the Morpheus control center for on-site field testing at JSC, the small 2-story building 18 that was formerly used for rooftop GPS testing and storage. The main upstairs room has a window that looks directly out onto the test area, making it highly suitable as the operations “front room,” configured with three rows of computer tables for operator workstations. An adjacent room serves as the “back room” for support personnel.

The operator workstations use GSFC’s Integrated Test and Operations System (ITOS) ground software. Like CFS, ITOS was developed as ground control and display software for GSFC space vehicles and has been made available to other projects at NASA. ITOS is individually configured on each workstation to display vehicle telemetry and information unique to each operator position.

Figure 3 – Typical Morpheus ground support equipment

During each test, the Morpheus Project streams mission telemetry, voice loops, and video from the testing control center to JSC’s Mission Control Center (MCC) over dedicated wireless and wired networks. From there, data and video can be made available to internal and external networks for NASA personnel and the general public.

A thrust termination system (TTS) is employed both for range safety and independent test termination purposes. Closing either of two motorized valves in the TTS will shut off the flow of liquid oxygen and methane to the engine and terminate engine thrust. These TTS valves are completely independent from the rest of the vehicle systems and commanded using separate Ultra High Frequency (UHF) radios. The commands to initiate thrust termination are sent from a control unit located in the operations center during any live engine testing.

Ground systems also include propulsion ground support equipment (GSE). The consumables required for an engine test include liquid oxygen, liquefied natural gas, helium, liquid nitrogen, and gaseous nitrogen. The power GSE is a portable ground power cart that is used to supply power to the vehicle until the test procedures call for a switch to internal vehicle power. The ground power cart uses heavy duty batteries and can provide up to 72 amp-hours of power for pre- and post-test activities. The mechanical GSE includes a rented crane for tethered or hot fire / hold-down testing. For tethered tests, an energy absorber is placed between the vehicle and the crane boom arm. The energy absorber is an aluminum piston and cylinder with cardboard honeycomb material that can attenuate up to 10,000 lb. This load attenuation protects the vehicle and crane structures in the event engine thrust needs to be terminated prematurely, causing the vehicle to drop to the end of the tether.

Ground systems also include a variety of transportation assets, provided primarily by JSC Center Operations.

C. Operations

The final element of the Morpheus system is Operations. Nine primary operator positions are staffed by team members: test conductor (TC), operator (OPS), propulsion (PROP), avionics, power and software (APS), guidance, navigation and control (GNC), ground control (GC), two range safety officers (RSO-1 and RSO-2), and the flight manager (FM). During tests with payloads aboard, another position may be included, such as one for ALHAT. Each position is certified through specific training.

Certification is also required for three pad crew (PAD) positions. PAD-1 is the pad crew leader, responsible for communicating directly with the test conductor during operations and ensuring each procedural step is executed at the pad. PAD-2 and

Figure 4 – Morpheus Control Center

PAD-3 provide support to PAD-1, and conduct all handling of cryogenic fluids and most other consumables.

On test days, many other JSC and Morpheus team personnel serve in various functions. JSC riggers support vehicle transportation and crane operations. Support personnel for each subsystem monitor data or help out during testing in the “back room” of the control center. Other team members stand by for potential troubleshooting if problems arise.

3. MORPHEUS TEST CAMPAIGN

Morpheus testing includes three major types of integrated tests: hot-fire, tether, and free-flight.

A. Hot-fire Testing

During hot-fire testing the vehicle is completely restrained from movement and the primary focus is to test the LOX/methane propulsion system. In this configuration a crane is used to suspend the vehicle above the ground to provide clearance for the vehicle exhaust plume. The vehicle is also constrained from below using straps anchored to the ground that prevent vertical and lateral vehicle motion.


Figure 5 – Morpheus in standard Hot-fire Test Configuration

Figure 5 shows the vehicle during test in the hot-fire configuration. The vehicle is suspended approximately 20’ above a concrete pad by a crane outfitted with shielding to prevent damage from flames or debris during the test firing. Additional restraints are attached below the vehicle made of nylon overwrapped with fireproof insulation or chains.

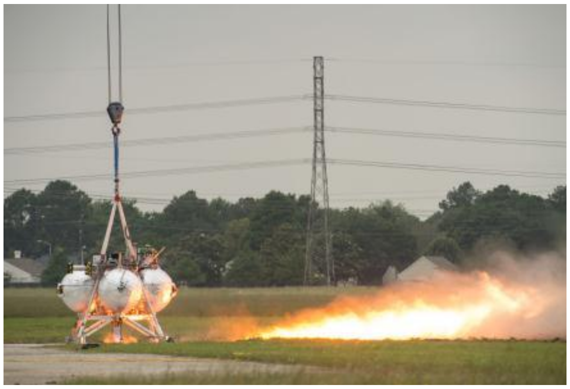


Figure 6 – Morpheus in Ground Hot-fire Test Configuration

The objectives for hot-fire tests include demonstration of the igniter, engine ignition, performance at varied throttle settings and burn duration tests. The Morpheus project test approach limits testing on a dedicated engine test stand and emphasizes a quick transition to integrated vehicle tests. Testing on the vehicle promotes optimization of engine performance for the actual vehicle propulsion feed system instead of the test stand system. It also allows gimbal sweeps to evaluate the integrated performance of the actuators under load. The majority of engine characterization is conducted on the vehicle, essentially making the hot-fire configuration the primary engine test stand for the Morpheus Project.

A second hot-fire configuration was also developed to test the thermal and vibroacoustic environments at liftoff. In this case, the vehicle remains static on the ground, chained to the launch pad. The engine is run for only a few seconds at maximum thrust to envelope any environments expected on an actual launch attempt. One such test of the ‘Bravo’ vehicle over a flame trench is depicted in Figure 6.

B. Tether Testing

For tether tests the vehicle is suspended from a crane as shown in Figure 4 to enable testing of the propulsion and integrated GN&C without the risk of a vehicle departure or crash. The goal of these tests is typically to ascend 5 to 15 feet vertically and up to 10 feet laterally and hover in place for a pre-programmed duration. Upon successful completion of the hover, the vehicle descends and “lands” at the end of the tether.

Due to the potential dynamic loads during tethered flight, a substantially larger 120-ton crane is used for this testing. An energy absorber in line with the


Figure 7 – Morpheus 1.5 ‘Bravo’ executing a Tether Test in July 2013

tether reduces the loads on both the crane and Morpheus vehicle and helps prevent damage to either asset.

Tether testing provides the first opportunity to perform integrated testing of the Morpheus vehicle with closed-loop GN&C. The primary objective of tether testing is to demonstrate 6 degree-of-freedom (DOF) GN&C for vertical translation, hover and simulated landing operations. An additional objective is to understand and rapidly refine the integrated performance of avionics, propulsion, and GN&C without risk of a vehicle crash.

C. Free-Flight Testing

Morpheus "free-flights" demonstrate the fully integrated flight capability of the vehicle with no restraints. Free-flight safeguards are automatic on-board aborts, remotely commanded aborts, as well as the redundant and independent TTS that can be activated by spotters who visually determine trajectory deviations. A variety of free-flight trajectories can be flown to incrementally build up to a fully functional Morpheus lander capable of flying planetary landing trajectories.

4. MORPHEUS 1.0 TEST CAMPAIGN

During the Morpheus 1.0 test campaign, a series of three hot-fire tests was conducted to refine propulsion system performance. This was also the first opportunity to test vehicle hardware and software together. Due to the fast pace of development, these tests were used as verification tests for numerous software routines.

The Morpheus team completed these three hot-fire tests in 8 days and successfully demonstrated all test objectives except for handover from propulsion to GN&C. The team quickly resolved all issues and confirmed solutions in subsequent tests, gaining valuable vehicle operations experience and confidence to proceed with tether testing.

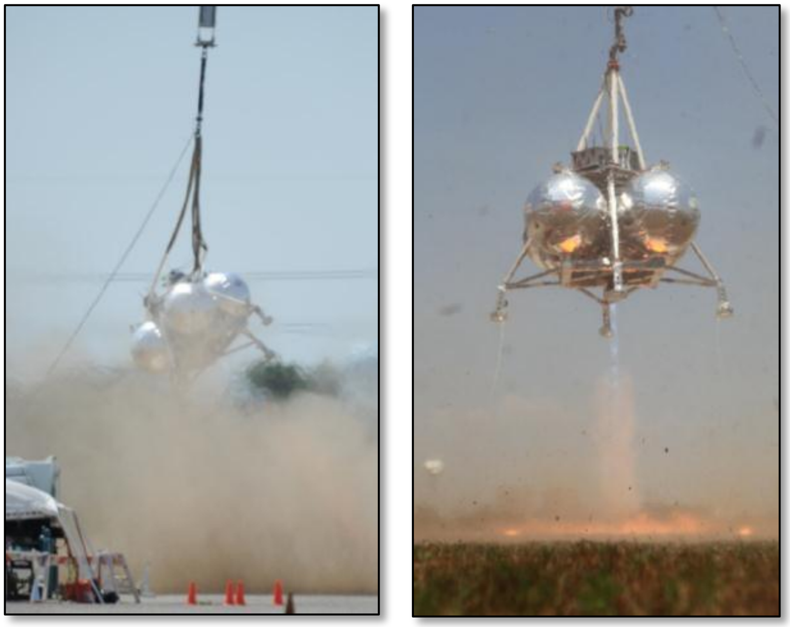


Figure 8 – Morpheus Tether Test 2 (TT2); and Tether Test 5 (TT5)

Immediately following the hot-fire tests, five tether tests were conducted between April 25th and June 1st, 2011, with the primary objective to demonstrate stable 6-DOF GN&C. The rapid schedule of the first four tests was driven by a demonstration flight planned for the JSC Innovation Day event on May 4th.

The most dramatic tether test in this test campaign was TT2. Immediately upon engine ignition, an H-bridge circuit controlling the throttle valve failed fully open (+100% throttle). The vehicle rapidly ascended and an asymmetric bungee arrangement caused a pitching moment. When the ignition sequence was complete and control was handed over to GN&C, the vehicle was already in an unrecoverable trajectory. To make matters worse, the GN&C system contained a 90-degree clocking error in an IMU coordinate frame, preventing it from stabilizing the vehicle motion.

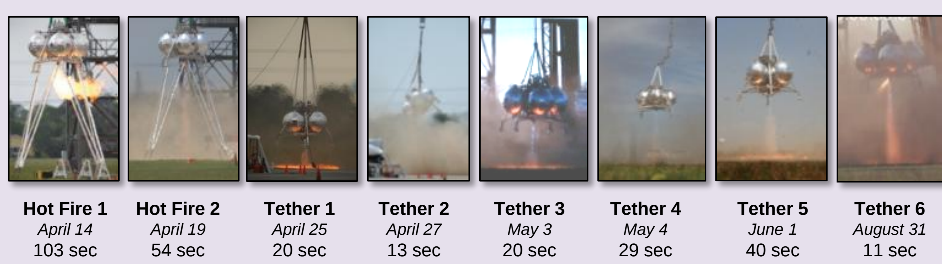


Figure 9. Morpheus 1.0 Test Summary

This uncontrolled motion continued despite on-board software and ground commands for soft and hard abort and engine shutdown. These primary abort methods rely upon shutting the throttle valve, which was stuck open. After

13 seconds of erratic “tetherball” flight, engine thrust was terminated by manual activation of the wired TTS.

The team would not have chosen such dynamic test conditions. Yet this “test failure” provided a training opportunity for the team to execute a safe abort, and identified key systems issues, enabling the team to improve the engine throttle valve design and correct the navigation frame transformation error. No vehicle or property damage resulted from this test, and the team turned around the VTB for another test in less than a week.

The vehicle was better behaved during TT5, successfully completing a full duration run with nominal engine shutdown after 42 seconds. Hover performance was improved, producing only a minor wobble with a period of approximately 3.2 seconds. The engine performed nominally and reached a steady-state temperature for the first time during VTB 1.0 testing. Testing of the 1.0 configuration came to an end when the HD3 engine suffered a burn-through event during throttle-up for tether test 6. A new engine design iteration, new avionics, GNC, software, and other upgrades were incorporated onto the vehicle to form the 1.5A vehicle assembly.

5. MORPHEUS 1.5 ‘ALPHA’ TEST CAMPAIGN

The Morpheus 1.5A test campaign began in February 2012. Three hot fire tests, one ground hot fire and fourteen tether tests were performed, accumulating over 870 seconds of runtime on the HD4 engine. The tether tests were opportunities for the design team to continue to characterize and improve the interaction between the GN&C and propulsion systems. Table 2 lists the test summary for Morpheus 1.5 ‘Alpha’.

After HF5 confirmed the performance of the new HD4 engine, the team began the assessment of the integrated VTB 1.5 performance in tethered hover tests. Notable tests include TT9, which revealed a GN&C algorithm issue that caused the vehicle to exceed the altitude constraint, leading to activation of the TTS to abort the test. TT9 proved the value of the in-line energy absorber and the very robust vehicle construction in preventing damage to VTB 1.5 as it dropped to the end of the tether.

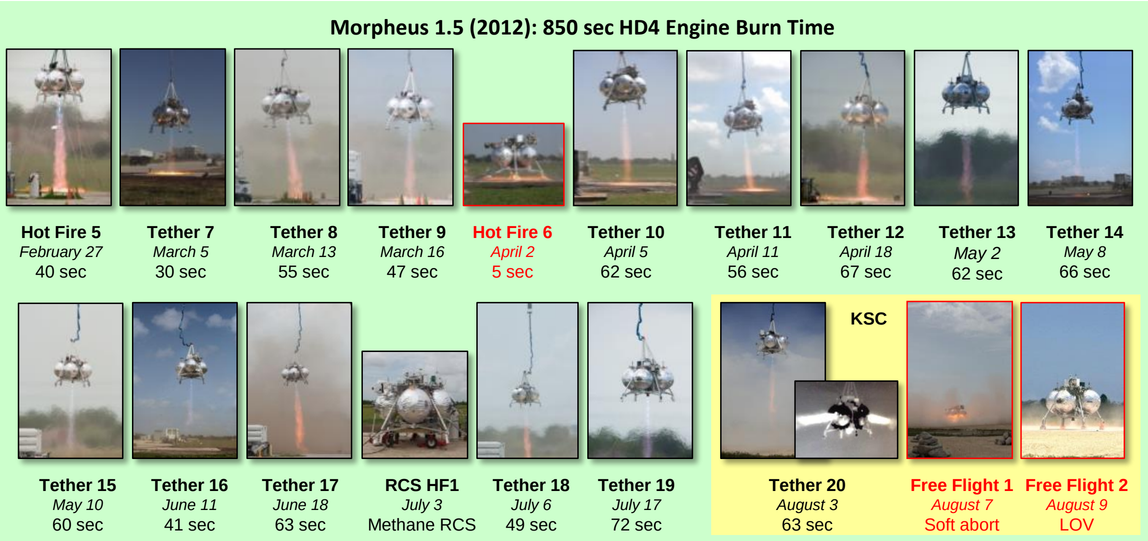


Figure 10. Morpheus 1.5 ‘Alpha’ Test Summary

As the first test of Morpheus sitting on the launch pad in liftoff configuration, HF6 provided valuable ground effects and overpressure data, and revealed that the footpads were insufficiently insulated. This test served as a proto-qual test, intended to envelope the environments expected to be experienced during free flight launches. Tether tests 10 through 15 demonstrated increasing vehicle controllability and stability with nominal engine shutdowns as the team refined GN&C and EMA parameters. With satisfactory vehicle performance, the ALHAT suite of sensors was integrated with the vehicle for two tether tests. This initial integration did identify some hardware and software timing discrepancies that required continued maturation once the sensors were removed from the vehicle.

With ALHAT integration testing complete, the team prepared for free flight testing by conducting one final tether test at JSC, shipping the vehicle to KSC, and then conducting a tether test at KSC’s Shuttle Landing Facility (SLF) to verify transportation did not impact vehicle readiness.

6. FREE FLIGHTS

A. Risk Posture

Heading into free flights at KSC, it was important for the project to maintain a consistent risk posture. The vehicle was built from the beginning as a single-string prototype vertical take-off and landing vehicle. That approach enabled the project to pursue lean development and make advances in design, testing and operations in a more rapid fashion. However, there are inherent risks to the vehicle using this approach. The project put forth significant effort in identifying and mitigating single-point failures that could cause loss of vehicle prior to heading to KSC. That included substantial subsystem-level testing, all of the tether testing previously described, and system-level protoqual testing, such as the ground hotfire test.

The primary exception to the single-string philosophy included safety systems in subsystems such as pressure systems and range safety. Pressure systems have redundant pressure relief components built in. There is also a dual-redundant thrust termination system (TTS) on board the vehicle that that includes 2 independent valves in the propulsion system, either of which can cut engine thrust on command. This exemplifies the project emphasis on safety, even in light of accepting additional risk to the test vehicle itself.

The purpose of the ground hot-fire test was specifically to envelope the environments expected during liftoff of a free flight. HotFire 6 did exactly that. The vehicle was outfitted with a variety of instrumentation, including accelerometers, microphones and thermocouples, and was chained to the ground launch pad. Upon ignition, the engine was throttled up to 100% and remained for 5 seconds to conservatively characterize the environment. Beyond this type of testing, there were no standard qualification tests of components due to the prototype nature of the vehicle.

In addition to the actual testing accomplished, it was important to ensure all stakeholders were fully aware of the risk posture for free flights. The loss of the Morpheus 1.5A vehicle was pre-declared a test failure and not a mishap as long as no personnel were injured or infrastructure was damaged. In this light, the loss of vehicle was considered an acceptable risk for the purpose of advancing our understanding of all of the components of integrated vehicle performance.

B. Free Flights 1 & 2

In preparation for the final demonstration flights with ALHAT, a hazard field – replicate of an area of the lunar surface – was constructed off the end of the SLF runway as the approach field for the Morpheus free flight testing. The initial test campaign at KSC, though, was intended to incrementally expand the flight envelope to demonstrate adequate vehicle performance before reintegrating the expensive ALHAT sensors.

On August 7, 2012, Free Flight 1 was aborted just after liftoff due to a faulty transient engine burn-through indication. The vehicle detected the indication and soft-aborted as designed – after rising less than a foot off of the pad. The erroneous indication was readily fixed, as was an issue identified with the crushable footpads used for impact attenuation on landing. In 24 hours, personnel at KSC designed and developed some thermal protection for the footpads to ensure they would last through any flight profile.

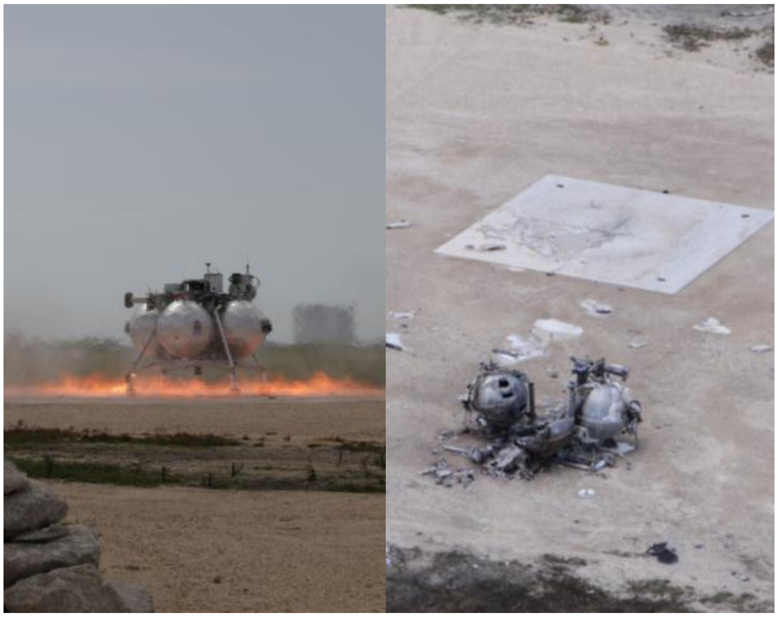
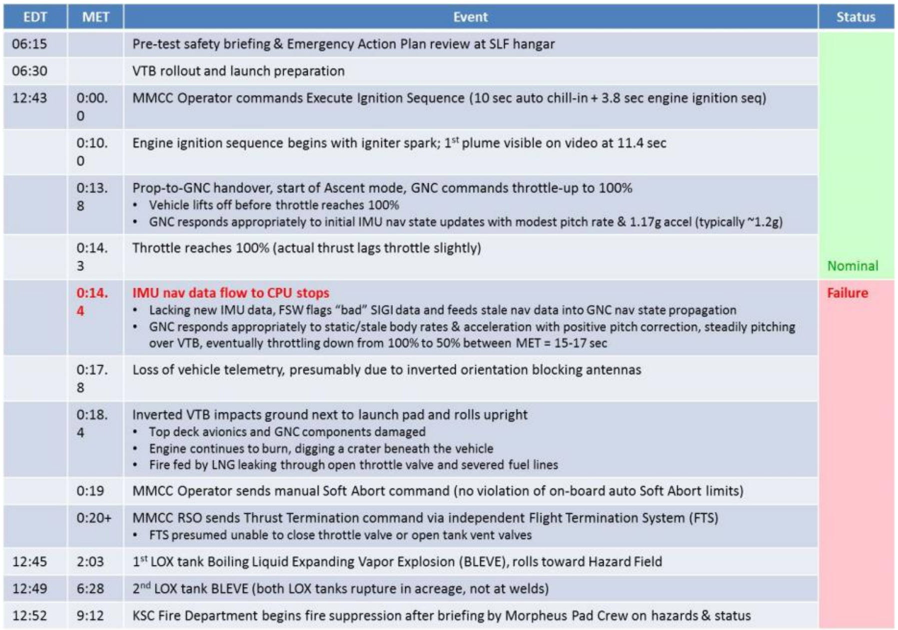


Figure 9 – Shuttle Landing Facility at KSC: Morpheus Free Flight 1at ignition; and Free Flight 2 after it crash landed.

Free Flight 2 was attempted two days later, on August 9. In this test, the data from the only active IMU was lost 0.6 seconds into flight, causing the vehicle to lose control and crash. The combined JSC/KSC team immediately executed the pre-rehearsed emergency action plan to protect personnel and property, so damage was limited to vehicle hardware.

The timeline of events during takeoff is shown in Table 1.

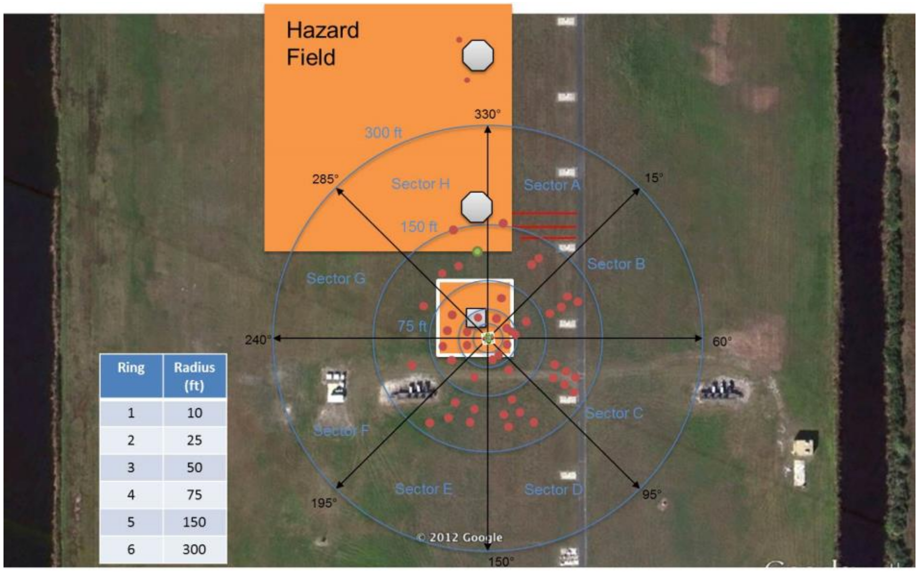


EDT	MET	Event	Status
06:15		Pre-test safety briefing & Emergency Action Plan review at SLF hangar	Nominal
06:30		VTB rollout and launch preparation	
12:43	0:00.0	MMCC Operator commands Execute Ignition Sequence (10 sec auto chill-in + 3.8 sec engine ignition seq)	
	0:10.0	Engine ignition sequence begins with igniter spark; 1st plume visible on video at 11.4 sec	
	0:13.8	Prop-to-GNC handover, start of Ascent mode, GNC commands throttle-up to 100% • Vehicle lifts off before throttle reaches 100% • GNC responds appropriately to initial IMU nav state updates with modest pitch rate & 1.17g accel (typically ~1.2g)	
	0:14.3	Throttle reaches 100% (actual thrust lags throttle slightly)	
	0:14.4	IMU nav data flow to CPU stops • Lacking new IMU data, FSW flags "bad" SIGI data and feeds stale nav data into GNC nav state propagation • GNC responds appropriately to static/stale body rates & acceleration with positive pitch correction, steadily pitching over VTB, eventually throttling down from 100% to 50% between MET = 15-17 sec	Failure
	0:17.8	Loss of vehicle telemetry, presumably due to inverted orientation blocking antennas	
	0:18.4	Inverted VTB impacts ground next to launch pad and rolls upright • Top deck avionics and GNC components damaged • Engine continues to burn, digging a crater beneath the vehicle • Fire fed by LNG leaking through open throttle valve and severed fuel lines	
	0:19	MMCC Operator sends manual Soft Abort command (no violation of on-board auto Soft Abort limits)	
	0:20+	MMCC RSO sends Thrust Termination command via independent Flight Termination System (FTS) • FTS presumed unable to close throttle valve or open tank vent valves	
12:45	2:03	1st LOX tank Boiling Liquid Expanding Vapor Explosion (BLEVE), rolls toward Hazard Field	
12:49	6:28	2nd LOX tank BLEVE (both LOX tanks rupture in acreage, not at welds)	
12:52	9:12	KSC Fire Department begins fire suppression after briefing by Morpheus Pad Crew on hazards & status	

Table 1 – Free Flight 2 Timeline

C. Debris Recovery

At the conclusion of emergency response activities, with the vehicle and all other hardware safed, the Morpheus team reassembled into a debris recovery team. Data was secured from the control center and from the vehicle where possible, as well as all video sources. The debris field was methodically mapped over two days and all debris recovered. A polar grid was established and debris was catalogued and weighed. Nearly all debris was contained within a 50m radius. Results of the debris assessment verified that the blast models used by the project to establish safe distances for personnel were indeed conservative. This data has been turned over to numerous interested parties to help refine various blast models that have been developed.



Ring	Radius (ft)
1	10
2	25
3	50
4	75
5	150
6	300

Figure 10 – Free Flight 2 Debris Map

The entire vehicle was lost, with the exception of a handful of parts that were recovered. The onboard SD card experienced too much heat damage for data recovery, but the APU Solid State Disk Drive data and DFI box were recovered. Since the engine continued to burn on impact, cryogenic propellants were flowing through it. As a result, the HD4 engine injector was recovered and reusable, and has been incorporated into the rebuilt engine currently powering the 'Bravo' vehicle.

D. Proximate Cause

It was evident immediately upon loss of the vehicle that the onboard IMU has stopped communicating with the control computer 0.6 seconds after liftoff. A thorough investigation confirmed this diagnosis. All evidence points to proper performance of the power and propulsion subsystems, and software performed exactly as designed throughout the brief flight. There were no indications of instrumentation loss beyond the IMU data and no evidence of structural failure. Winds and weather were benign at the time of flight.

As a result, the proximate cause was isolated to the loss of navigation data, required by the vehicle to maintain its navigation state and attitude knowledge. Without that data, the vehicle is flying blind and responding only to its last known state and attitude. However, there are several components within the string of navigation data, and forensics did not identify with certainty the absolute cause.

The IMU instrument itself, 1553 bus hardware and couplers, wiring, computer interface, and software are all potential components that could have produced the flight signature. Forensic analysis of the recovered Avionics Power Unit (APU), which includes the primary computer, identified good continuity in most harnesses even after the crash. Such study could not be completed on the other components as they were unrecoverable.

The investigation into the proximate cause was guided by a thorough fault tree assessment. The results of the investigation yielded the probable failure as a hardware component failure outside of the APU most likely as the result of high vibroacoustic environments at liftoff. The affect could have been acute or the accumulation of damage due to repeated exposure to the vibration environment.

7. FINDINGS AND CORRECTIVE ACTIONS

The engineering investigation described herein was accomplished over three months and incorporated inputs from the entire Morpheus team as well as independent expert reviewers. The findings and corrective actions that resulted from the investigation are summarized in Table 2.

8. MORPHEUS 1.5 'BRAVO' UPGRADES

The loss of Morpheus 1.5 'Alpha' resulted in a rebuild effort to return to testing. 70 upgrades were approved for incorporation into the 'Bravo' vehicle, as well as GSE, operations and test facilities. Rebuild efforts began in earnest in October 2012 with the first integrated hot fire test completed six months later. To date, two hot fire tests, a ground hot fire over a newly installed flame trench, and 8 tether tests have been conducted.

Figure 10 – Morpheus 1.5 'Bravo' executing a translational Tether Test in August 2013. Mars soil simulant was deployed on the launch pad to study plume impingement for the Mars 2020 program.

The knowledge gained in testing the 'Alpha' vehicle significantly improved the performance characterization of the 'Bravo' vehicle once its testing began. However, there were a number of sticking points that needed attention. For one, 'Bravo' is a 200lb heavier vehicle and its engine produces 800lb more thrust than its predecessor. The change in mass properties, combined with some plumbing changes, led to an unacceptable susceptibility to propellant imbalances that caused a number of soft aborts during early tether testing. The abort box is a very stringent 4m for tether testing, to prevent tether interaction and ensure crane protection. Tuning of guidance and control parameters eventually overcame the problem, allowing tether testing to proceed unhindered.

Improvements for 'Bravo' vehicle operations also included significantly enhanced flight simulation capabilities. Reliable simulation tools afforded the project the opportunity to predict vehicle performance under more risky tether flight profiles. Planned testing progressed from simple vertical hovers (all that was accomplished with 1.5A in 2012) to multi-level vertical motion with lateral translations of up to 3m. This expanded capability enabled the testing of all different versions of gain scheduling through all phases of flight, which allowed the project to 'test like you fly' in preparation for future free flights at KSC.

Integration with the ALHAT instruments was repeated with the 'Bravo' vehicle during tether testing. Integrated performance was significantly improved from 2012, with nearly all discrepancies resolved and demonstrated HDS pointing accuracy within 0.15 degrees. Additionally, the project collaborated with the Mars 2020 Program from the Jet Propulsion Laboratory by incorporating a plume impingement study using Mars soil simulant during a tethered test. A photo taken shortly after ignition is included as Figure 9.

One final new test is planned before the team moves to KSC to begin free flight campaigns. A Ground Takeoff and Landing (GTAL) test, while still constrained via tether, will be conducted at JSC in September 2013. The concept is to buy down risk by demonstrating liftoff over a flame trench followed by a nominal translation, descent and landing back on the ground. The tether only provides range safety and will minimize any damage if there is a problem during the test. This will be the last test planned at JSC before the vehicle is moved back to KSC for testing at the SLF.

Table 2. Free Flight 2 Crash Findings and Corrective Actions

#	Probable or Possible Cause or Contributor	Corrective Action
1	**Vibro-acoustic environment near ground** repeatedly exceeding component limits and eventually causing fatigue failure during FF2	**Reduce vibro-acoustic environment** a. **Vibe isolation** for key components (e.g. IMU(s) & 1553 bus) • IMU risk: misalignment due to plastic deformation of vibe isolator • IMU challenge: attenuate high frequency vibe but not lower FCS frequencies b. **Relocate IMUs** away from center of top deck toward primary structure c. **Flame trench** for ground ignitions at JSC and KSC (assuming feasibility) • May increase effective launch altitude by roughly a body length, reducing launch vibration by up to an order of magnitude • Landing vibration becomes stress case, but is roughly half magnitude of current launch vibration due to half throttle, and occurs while descending near touchdown d. **Leverage NASA vibro-acoustic expertise** to supplement team experience
2	**Non-flight components** not sufficiently robust to environment (1)	**Increase component robustness** a. **Use PA1 SIGI flight unit** • Designed for high vibration PA1 environment • Perhaps more robust than "flight-like" ISS SIGI development unit b. **Procure higher quality 1553 bus components with greater robustness to high vibe environments** c. **Use both channels of 1553 bus** • 1553 bus will automatically switch between channels A & B as necessary, and can report channel usage to CPU
3	**Workmanship** QA provided insufficient robustness for environment (1)	**Improve workmanship quality assurance/control** a. **Crew Chief** provides tighter control over vehicle access and components b. **Wiring/Cabling Subsystem Lead** implements best practices (e.g., strain relief) and focuses upon quality improvements & assurance c. **Certified wiring technicians** for build, installation and inspections
4	**Production imperfections** in primary components reduced robustness to environment	**Improve system quality and verification** a. **Higher quality components** (e.g., connectors, cables) b. **More verification testing** (e.g., SIGI vibe testing, tethered liftoff test)
5	**Accepted single-string IMU risk**	**Dissimilar, non-colocated backup IMU(s)** a. **Test backup IMU down-mode** and soft abort logic b. **LCC requirement** for operational backup IMU(s)

9. CONCLUSIONS

NASA's Morpheus Project has developed and tested a prototype planetary lander capable of vertical takeoff and landing, designed to serve as a testbed for advanced spacecraft technologies. The 'Alpha' version of the Morpheus vehicle successfully performed a set of integrated vehicle test flights including hot-fire and tether tests, but was lost during the second free flight test at KSC. The test failure investigation identified a proximate cause as the loss of navigation data most likely due to excessive vibro-acoustic environments. A number of contributory factors were also identified and discussed, with appropriate corrective actions.

In early FY13, Morpheus rebuilt a 'Bravo' vehicle after loss of the 'Alpha' vehicle, and made a number of upgrades and improvements to the vehicle and ground subsystems, including integration of the Autonomous Landing and Hazard Avoidance Technology (ALHAT) Project's hardware and software components. These upgrades will provide improved performance, expanded capabilities, and better robustness for an extended test campaign that will culminate in high energy trajectories that simulate a landing approach on a lunar, asteroid or planetary surface. The initial test campaign at JSC will be followed by free flights and high energy trajectories at KSC.

BIOGRAPHIES

Jennifer L. Devolites *- Ms. Devolites graduated from Texas A&M University with a Bachelors Degree in Aerospace Engineering. She has worked at NASA JSC for 21 years in a number of technical and management roles on projects including Simplified Aid for Extravehicular Activity Rescue (SAFER), Autonomous Miniature Robotic Camera (AERCam), Internatlonal Space Station Guidance, Navigation and Control (ISS GN&C), X-38, Exploration Technology Development Program Automated Rendezvous and Docking Sensor Technology Project (ETDP AR&DSTP), and Orion GN&C. She has served as the systems engineering and integration lead for Project Morpheus since 2009.*

Jon B. Olansen, PhD *– Dr. Olansen serves as the Project Manager for the Morpheus Project. He began his career as a Space Shuttle flight controller, supporting 32 missions and logging >4200 hours in Mission Control. Jon earned his B.S. in Aerospace Engineering and M.S. in Mechanical Engineering from the University of Notre Dame. He obtained his Ph.D. in Mechanical Engineering (Biomedical Focus) as a National Instruments Fellow at Rice University, where he specialized in biomedical experimentation in electrophysiology and cardiopulmonary hemodynamics. He has published several journal articles related to his research and authored a reference book on biomedical instrumentation. He returned to NASA to represent the Astronaut Office in the design, development, and operation of human life sciences experiments destined for the International Space Station. Dr. Olansen has since held a number of positions of increasing responsibility including tours in Safety & Mission Assurance, the Shuttle Program Office and the Exploration Systems Mission Directorate at NASA Headquarters, before undertaking his current role.*

Stephen R. Munday *– Mr. Munday serves as the Deputy Project Manager for the Morpheus Project. His NASA career spans 26 years as a lead engineer, technical board chairman, system manager, and international technical liaison for various NASA programs including the X-38 Crew Return Vehicle, Space Shuttle, Orion Crew Exploration Vehicle, and International Space Station (ISS). His engineering expertise is primarily in the fields of aerodynamics and GN&C. Prior to joining the Morpheus team, he spent 4 years helping to manage NASA's Moscow Technical Liaison Office in Russia's Mission Control Center and in the Baikonur Cosmodrome in Kazakhstan on behalf of the ISS Program. Mr. Munday holds an M.S. degree in Aerospace Engineering (G&C focus) from the University of Texas in Austin, an M.S. in Computer Engineering from the University of Houston at Clear Lake, and a B.S. in Aerospace Engineering (aerodynamics focus) from the University of Missouri – Rolla (now the Missouri Univ of Science & Technology).*