NASA Innovation Award 2014
Nomination Cover Pages

1. Nominee/Activity: Morpheus Project Team
2. Program/Project Manager: Jon B. Olansen, Ph.D.
3. Award Category (select appropriate box) **X Lean Forward; Fail Smart** ☐ **Champion of Innovation**
4. Citation: For Successful Design, Development and Execution of the Morpheus 2013/2014 Flight Test Campaigns at JSC and KSC
5. COR: Jeff Dutton (JETS COR): JSC/EA55;
6. Team Members: **JSC Project Management** Jon B. Olansen, PhD: JSC/EA52 Stephen Munday: JSC/EA52 Jennifer L. Devolites: JSC/EA53 All team members included in attachment.

MORPHEUS PROJECT
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The Morpheus Project began in earnest in June of 2010 as a lander technology development activity that could eventually support human and robotic missions to any surface. The most visible aspect of the Morpheus Project is the autonomous, reusable, rocket-powered, terrestrial vertical test bed (VTB), which provides a platform to mature, refine, and demonstrate advanced technologies in a relevant flight environment.

View from the KSC Shuttle Landing Facility at sunrise

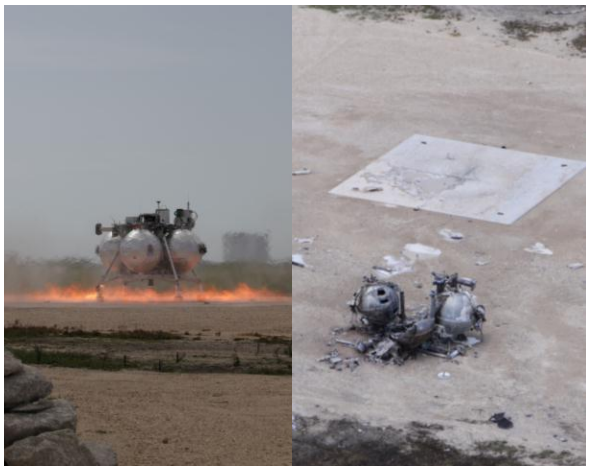
The Morpheus Project was challenged to provide this vehicle, the necessary ground support infrastructure, and operations capability to conduct flight tests using a lean development approach of a small team, rapid testing and turnaround, innovative partnerships and minimal resources.

Over four years, the project has spanned a total project life cycle from concept of operations through flight operations and sustaining engineering, with multiple prototypes and iterative design and development. In this time, the Morpheus project has built 2.75 nearly identical prototype vehicles, and conducted 60 flight tests: 12 static hot fires, 34 tether tests, and 14 free flights. The final five free flights at KSC successfully reached an altitude of 245 m and traveled 800 m downrange to a land safely in the hazard field with the ALHAT components integrated on board.

ALHAT Hazard Detection System mounted on the Morpheus 'Bravo' vehicle

The achievements of the project are a testament not only to the dedication and perseverance of the personnel that have made up the Morpheus team for four years, but also the enlightened attitude of NASA management to allow appropriate risk-taking and the use of test failures to ultimately succeed. This was best exemplified by the response to the loss of the first Morpheus vehicle.

On August 9, 2012, during the 27th integrated test and 2nd free flight attempt at Kennedy Space Center, the Morpheus 1.5 "Alpha" vehicle crashed shortly after takeoff. The entire vehicle was lost, with the exception of a handful of parts that were recovered for reuse. [Most notably, the HD4 engine injector was recovered and incorporated into the rebuilt engine currently powering the 'Bravo' vehicle, which recently reached 3000 seconds of cumulative engine firing time.] The cause of the crash was isolated to the loss of navigation data shortly after liftoff.



Morpheus 'Alpha' vehicle Free Flight 1at ignition; and Free Flight 2 after it crash landed.

Prior to beginning Morpheus flight tests, damage or loss of test hardware was pre-declared as a potential test outcome, not a more formal "mishap", and this risk had been well communicated up through the NASA management chain. As a result, Agency leadership immediately recognized the test nature of the failure and reiterated their endorsement of the project. NASA Administrator Bolden discussed the "fail forward" nature of Morpheus and its benefits in an open letter to Agency personnel on April 19, 2013. "No one likes to lose equipment, but we recognized that failure is part of the price of learning and acted accordingly. As long as we ensure that our people are protected we can manage and tolerate failures as part of the price of progress."

With leadership support, the team gathered at the crash site the next day and began to forge their forward path. Within two months, 70 design upgrades were developed, reviewed and approved for implementation in the buildup of the "Bravo" vehicle, associated ground support equipment, operations and test facilities. Some critical hardware and instrumentation would get redundancy, more advanced

fault detection and response algorithms would be incorporated, a flame trench was designed and deemed mandatory, and numerous other ground systems and operations procedures would be modified. Rebuilding efforts began in earnest in October 2012, with the first integrated hot fire test completed six months later. The knowledge gained in testing the 'Alpha' vehicle significantly improved the performance of the 'Bravo' vehicle once its testing began. A series of progressively more ambitious free flights were successfully completed at KSC between December 10, 2013 and May 28, 2014.

Morpheus rises above the KSC SLF during FF13

For Morpheus, lean development has been a rapid prototype development and test philosophy that emphasizes learning through frequent test activities. Off-nominal performance in a test would yield design improvements to hardware, software or operations that were quickly implemented and tested to see if they indeed improved performance. As a result, since April 2011 the project has executed sixty propulsive flight tests with two vehicles, yielding advancements in design, integration and operations, while generating copious amounts of data for continued analysis.

Morpheus Control at KSC during FF4

A key to lean development is accepting appropriate risk; the project must manage appropriate and acceptable risk, acceptance of "failure", and expectations of "success" in technology development. Heading into free flights at KSC, it was important for the project to maintain a consistent risk posture. From the very beginning, Morpheus vehicles were built as single-string, vertical take-off and landing prototypes. That approach enabled the project to pursue lean development and make advances in design, testing and operations in a more rapid fashion than many traditional projects. 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, tether testing, and system-level protoqual testing.

To be clear, this risk acceptance applies only to technical performance of the vehicle system. Hazards to personnel safety or infrastructure are managed at a much higher level of rigor, commensurate with all other activities done within the Agency. The primary exception to the single-string philosophy included safety measures in subsystems such as pressure systems and range safety. Pressure systems have redundant pressure relief components built in. The dual-redundant thrust termination system (TTS) on board the vehicle includes two independent valves in the propulsion system, either of which could cut engine thrust, each commanded by an independent range safety radio link. This exemplifies the project emphasis on safety, even while accepting additional risk to the test vehicle itself.

Engineers learn best by doing, by working hands-on with hardware and software, by designing, building and testing systems on an integrated flight vehicle. In just a few years, Morpheus and ALHAT have provided a prolific training ground for engineers and technical and project leaders. Lean development, rapid prototyping, emphasizing testing over analysis, allowing engineers to fail-forward to success—these tenets can enable not only lower costs and faster schedules, but, most importantly, more capable employees.

The dedication, innovation and "dare to try" reduced life-cycle methods this team utilized are atypical for human spaceflight development and allowed rapid improvements of the Morpheus and ALHAT systems that, now developed and tested, can be leveraged for future agency missions and objectives. With Morpheus, we have sought to balance risk with the opportunity for rapid advancement of technologies that will benefit the future of human space exploration. The spectacle of the free flights at KSC is evidence of the benefits of such an approach!

Morpheus liftoff