Demo Flight 2
Flight Review Update

Released by Space Exploration Technologies Corp on June 15, 2007

For questions, contact SpaceX.

1 Overview

On March 20, 2007 (PST) Space Exploration Technologies (SpaceX) launched Demo Flight 2, the second demonstration flight of the Falcon 1 launch vehicle. The mission was sponsored by the Defense Advanced Research Projects Agency (DARPA) and the US Air Force (USAF). Primary mission objectives were demonstrating responsive launch operations, gathering flight data and retiring technical risk prior to the first operational flight to launch the TacSat-1 spacecraft.

The primary mission objectives for the Demo Flight 2 mission, both programmatic and technical, were met by this return to flight. The vehicle attained a peak altitude of 289 km, 5.1 km/s maximum velocity and remained in the center of the intended ground track throughout flight. An upper stage control anomaly, however, ultimately prevented it from reaching orbital velocity, an important, but secondary mission objective.

This mission also demonstrated a highly autonomous ground control system and rapid recycle from a hot-fire abort to launch in under 70 minutes. On launch day, the first countdown was autonomously aborted by control software at T-0.5 seconds, when it detected that engine chamber pressure was ~0.5% under the designated threshold. After a partial de-tank and re-tank to warm the fuel, the vehicle was launched on the second attempt.

Significant achievements for Demo Flight 2 include successful demonstration of:

- ✓ Ground control & support systems, including control software, highly automated operations & autonomous abort
- ✓ Rapid response capability – launched within 70 minutes after hot launch abort
- ✓ 1st stage performance and control from lift-off through MECO
- ✓ Vehicle structural performance & margins through lift-off, transonic & max-Q
- ✓ Stage separation
- ✓ 2nd stage ignition
- ✓ 2nd stage engine performance in vacuum
- ✓ Fairing separation
- ✓ Guidance, navigation & control performance through T+~475s, including all flight regimes
- ✓ Flight software
- ✓ Launch & flight environments: thermal, shock & vibration
- ✓ Aero-thermal and base-heating (both stages) protection

Although eight anomalies have been identified (described in Section 3) by post-flight data analysis, the upper stage control anomaly was the only known issue that prevented this mission from achieving orbit. Had it not been for the upper stage control anomaly, all indications are that Demo Flight 2 would have reached its intended orbit:

- Before partial loss of control, the vehicle retained ample performance margin to reach the desired orbit within bounds specified by customer
- Even after partial loss of control, the vehicle continued towards its intended orbit, albeit in a corkscrewing motion around the nominal flight path
- If the instability had not resulted in a roll that moved propellants away from engine inlet, the vehicle retained ample performance margin to reach orbit

2 Vehicle Performance Assessment

Prior to the upper stage control anomaly causing second stage engine flame out, the vehicle retained ample margin to reach orbit. Due to saturations in guidance algorithm, vehicle would have achieved 324 x 685 km at orbital insertion, which is well-within stated insertion accuracy of ±10 km.

Vehicle performance was within an acceptable range until T+265 seconds. At this point, an oscillation in the upper stage control system began to appear. This instability grew over time until about T+474 seconds, engine shutdown.

3 Anomalies

There were eight significant anomalies identified during analysis of flight data, including the upper stage control issue. Addressing and correcting these items constitute a constraint on the next flight of the Falcon 1 vehicle. These anomalies are summarized below.

Stage 2 LOX Quick Disconnect (QD) Failed to Disconnect at Liftoff
This resulted in the LOX QD panel (with QD) and ~2" of LOX fill line separating from vehicle. An internal LOX check-value prevented any loss of propellant from the vehicle and there is no evidence of other damage to the stage or that this contributed in any way to other flight anomalies or observations. SpaceX is working with the QD vendor to address the design.

Stage 1 LOX, Fuel, and Electrical QD's Poor Disconnect at Liftoff
The LOX and fuel QDs each traveled several inches further with the vehicle than intended before separating nominally at the connectors. The Electrical QD lanyard broke before separating at the ground-side connector back-shell. There is no indication these contributed in any way to flight anomalies or observations. SpaceX will redesign the QD panel.

Stage 1 Trajectory Performance
This anomaly is two-fold. First, an incorrect propellant utilization file was loaded into the engine computer. This error caused the engine mixture ratio to be lean on lift-off and rich at altitude. Therefore, thrust was slightly lower than intended early in the flight, resulting in increased gravity losses and causing the first stage trajectory to be slightly lower and slower than predicted. SpaceX has adjusted its configuration management system to ensure that this will not recur.

Separately, the 1st stage LOX tank ullage pressure dropped below nominal near the end of the burn, causing the LOX pump to cavitate (benignly). This issue has been addressed by adjusting tank pressure set-points and regulation.

Stage 2 Propellant Utilization (PU)
It is apparent from flight data that PU function did not operate correctly during the 2nd stage engine burn. If the upper stage control anomaly had not occurred, this anomaly would have resulted in higher residual propellant at the end of 2nd stage burn, decreasing the vehicle's performance margin. This is still under investigation. It may be a secondary effect of other anomalies.

Stage Separation Re-contact
The nozzle of the Kestrel engine made contact with the interstage section as they separated after Main Engine Cut Off (MECO). The stage separation pyro-bolts and pneumatic pushers functioned correctly and were not a contributing factor.

The re-contact occurred due to higher than anticipated rotation rates, both of the combined vehicle stack prior to separation, and of the 2nd stage after separation. This rotation was caused partly by the Merlin engine pointing slightly off center-of-mass at shutdown. However, analysis now indicates that a majority of the rotation was caused by increased aerodynamic forces acting on the 2nd stage and fairing, due to the vehicle being lower than expected during stage separation and at a high angle of attack.

With corrections to the mixture ratio and helium pressurant margins, as well as improved thrust and Isp from the Merlin 1C engine that will be used in all future flights, the separation altitude will be considerably higher and aerodynamic forces will not be a factor. Merlin shutdown will also be initiated at a lower acceleration.

Marmon Clamp Joint Separation Anomaly at Fairing Jettison

The Marmon band that clamps the bottom of the payload fairing until jettison is retained by two redundant pyro-bolts. Telemetry indicates both bolts fired, but on board video shows that the two halves of this band appear to be joined as it falls away from the vehicle. The other bolt did fire and the fairing separately properly. This anomaly is still under investigation.

Upper Stage Control Anomaly

An oscillation appeared in the upper stage control system approximately 90 seconds into the burn. This instability grew in pitch and yaw axes initially and after about 30 seconds also induced a noticeable roll torque. This roll torque eventually overcame the 2nd stage's roll control thrusters and centrifuged the propellants, causing flame-out of the Kestrel engine. There is high confidence that LOX slosh was the primary contributor to this instability. This conclusion has been verified by third party industry experts that have reviewed the flight telemetry.

Falcon 1 did not use slosh baffles in the second stage tanks, as simulations done prior to flight indicated the slosh instability was a low risk. Given that in space there are no gust or buffet effects, the simulations did not take into account a perturbation, as occurred due to the hard slew maneuver after stage separation. Extensive 2nd stage slosh baffles will be included in all future flights, as is currently the case with the 1st stage.

1st Stage Location and Recovery

The 1st stage was not recovered as planned, however this was neither a primary nor secondary customer objective. The search by the recovery vessel discovered no sign of the stage and no signals were received from the electronic, sonar and visible location aids. Telemetry was received from the 1st stage until it dropped below the horizon, but it was still at ~50 km altitude at that time and the parachute nominally deploys at 4 km.

There is no data to confirm whether or not the parachute system operated and the stage landed intact. The range provided an inaccurate landing location (aerodynamic drag was neglected in their calculation) to SpaceX, resulting in the recovery ship being approximately 20 miles away from the true landing location. The onboard GPS locator for the 1st stage was not functioning, so there was no way to take corrective action. SpaceX will make the GPS location function triple redundant and increase robustness of the stage to protect against potential thermal damage on reentry.

4 Frequently Asked Questions

Did the hot-fire abort during the previous launch attempt have any effect on any of the anomalies or observations?

No relationship between the March 19 (PST) abort and the above mentioned anomalies has been found. The engines are designed and tested to be re-started in rapid succession. All vehicle and ground systems showed nominal prior to the decision to attempt launch again.

What caused the abort of the first launch attempt?

Cold fuel caused the combustion chamber pressure to be approximately 0.5% below the engine computer abort limit after engine start. Investigation revealed that the fuel was colder than normal due to the previous day's launch attempt. Draining back colder than normal fuel into insulated tanks did not allow sufficient time to warm to expected levels for the next day's operation. The solution is to add warming to the fuel conditioning regimen and verify fuel temp in the T-2 hours launch commit criteria.

5 Conclusions

This mission represents a large step forward for SpaceX and the Falcon 1 launch vehicle. Although short of complete success, a significant majority of mission objectives were met from both a programmatic and technical perspectives. Open issues were identified, but no items are anticipated to require major re-designs to fix.

Obtaining flight data from the vehicle was the primary objective of this test flight and was clearly achieved based on both the quantity and quality of performance and environmental data. Additionally, concept of operation, procedures, ground systems and control automation systems were validated. A rapid response capability was also demonstrated with a hot-fire abort within 70 minutes of launch.

Stage 1 recovery was not demonstrated and represents the only operational domain from which data was not attained by this mission. Additionally stage 2 coast and Kestrel re-start was not demonstrated, nor was Payload simulator deployment. Eight anomalies were identified which will be addressed prior to the next mission.