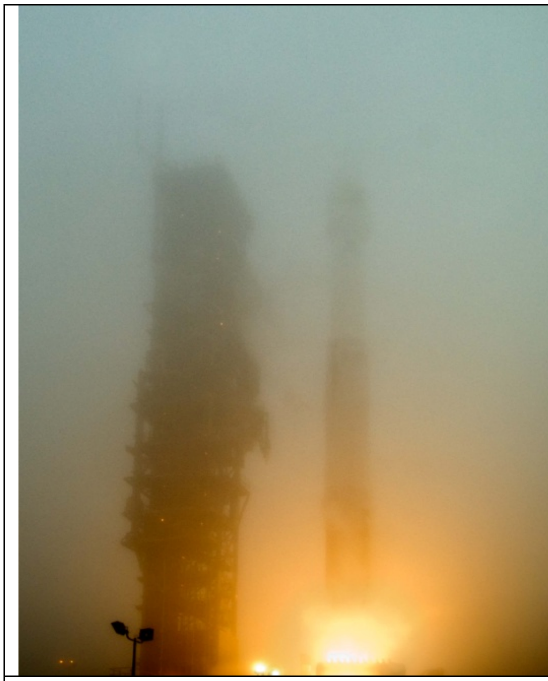
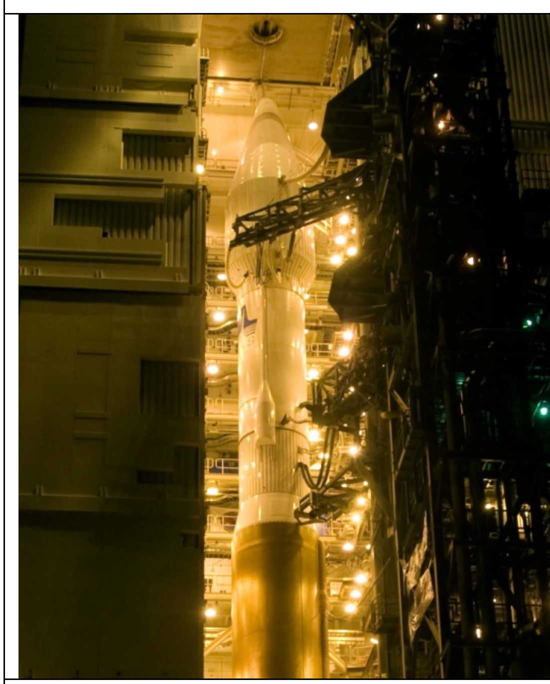
Successful Flight Demonstration Conducted by the Air Force and United Launch Alliance Will Enhance Space Transportation

The Air Force and United Launch Alliance (ULA) successfully completed numerous on-orbit cryogenic-fluid-management demonstrations on the Atlas V AV-017 mission following successful insertion of the DMSP-18 spacecraft. Six distinct demonstrations were performed specifically designed to improve our understanding of propellant settling and slosh, pressure control, RL10 chilldown and RL10 two-phase shutdown operations. Lessons learned will guide further upgrades to ULA's current Atlas and Delta cryogenic upper stages improving performance and allowing longer, more demanding missions. These results also directly benefit current operation of the Air Force Evolved Expendable Launch Vehicle fleet, development of ULA's planned Advanced Common Evolved Stage and other cryogenic systems.



Lift-off of AV-017 carrying the DMSP satellite for the Air Force.

Special research and development instrumentation was added to Centaur, the Atlas cryogenic upper stage, to support the demonstration including temperature measurements on the LH2 sidewall, forward bulkhead, LH2 feedline, RL10 pump housing and aft bulkhead components. The demonstrations commenced once Centaur had maneuvered a safe distance away from DMSP-18 to ensure no risk to the spacecraft. The Centaur disposal burn was delayed by 2.4 hours to allow for the low acceleration demonstrations. The disposal burn itself provided a unique opportunity to perform demonstrations without an attached payload. The light weight of DMSP-18 allowed 12,000 lbs of remaining LO2 and LH2 propellant, 28% of Centaur's capacity, for the demonstrations.

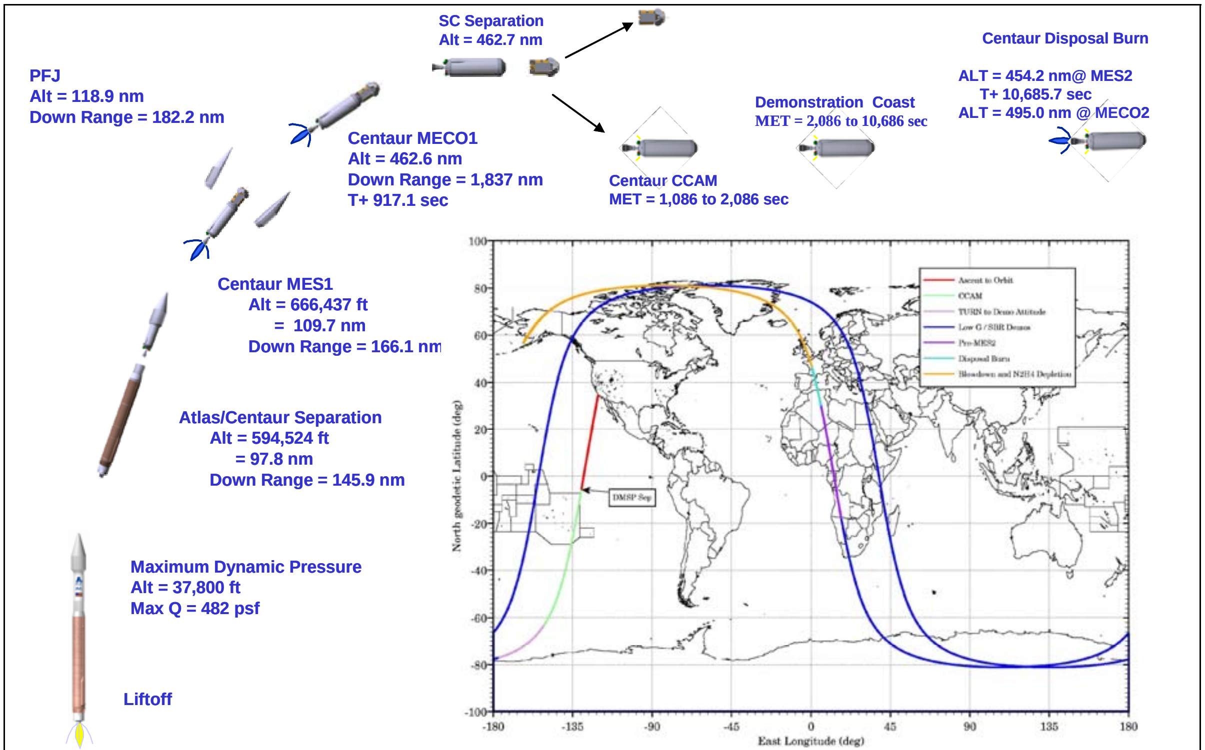


Centaur's sidewall was painted white and numerous dedicated instruments were added to support the on-orbit CFM demonstrations.

A preliminary data review of the demonstrations showed very favorable results. The majority of instrumentation worked properly, providing a wealth of data.

1) **Low-G Settling Demonstration:**

Centaur and other cryogenic space propulsion systems, such as the Delta IV second stage and Saturn V's S-4B stage, use on-orbit settling to separate liquid from gas. This separation is



A 2.4 hour post-spacecraft mission extension was added to the DMSP-18 launch to allow for a number of on-orbit demonstrations.

critical, enabling the stages to vent pure gas to control tank pressure. The required magnitude of settling acceleration directly affects the stage performance and maximum coast duration. For this demonstration, Centaur was settled by pulsing its four hydrazine thrusters at a reduced duty cycle to provide half of the acceleration that is typically used to support Centaur's longer coast missions. Lower duty cycle settling reduces the hydrazine consumption rate, allowing longer mission durations.

Results from the sidewall and bulkhead temperature measurements show that LH2 remained settled for the majority of the phase. A slosh wave did briefly cool the forward bulkhead after initially achieving the lower settling level, but the LH2 remained adequately settled for the remainder of the demonstration. The short sloshing period can be accommodated on future operational missions by inhibiting venting during the start of a coast. Ultimately, this lower acceleration level is shown to adequately support future long coast missions.

2) **Solid-Body-Rotation Settling Demonstration:**

For coasts longer than about 15 minutes, Centaur is rolled around its longitudinal axis to ensure uniform heating. Typically, the roll direction is regularly reversed to prevent solid body rotation of the propellant. For this demonstration, Centaur maintained a single roll direction to ensure solid body rotation. Following the low axial settling period, settling thruster firing was terminated with the objective to demonstrate that low level centrifugal acceleration could adequately retain liquid slosh. The liquid slosh must be kept sufficiently damped such that the hydrogen vent port, located on the forward door near the tank centerline, remains clear of liquid.

Initial post flight review of the attitude control thruster firings indicates that the solid body rotation did not induce nutation affects that would adversely affect future missions. Likewise, Centaur hydrogen tank venting and bulkhead temperature measurements confirm that the centrifugal settling maintained adequate liquid control and that disturbances caused by gaseous hydrogen and oxygen venting had no negative mission impact. Initial flight review indicates that centrifugal settling is promising, but the on-going detailed data review will be required to determine if it is beneficial for future flights.

3) **Oxygen Venting on-Orbit:**

Centaur's oxygen vent is not balanced so oxygen venting produces a torque on the vehicle. This is not a problem during current missions since Centaur does not vent on-orbit, however, longer duration missions in the future may require on-orbit oxygen venting to control tank pressure. This demonstration was designed to determine both oxygen and hydrogen liquid propellant management characteristics and vehicle control with the asymmetric force generated during oxygen venting.

Oxygen venting was conducted during both the low acceleration and centrifugal settling demonstrations. Results show that the LH2 remained settled during the low-g settling phase. No adverse propellant motion or vehicle control issues were observed. Following the GO2 vent during the Solid-Body Rotation settling phase, LH2 sloshing was observed on the forward bulkhead as predicted. If future missions utilize solid body rotation settling we may need to inhibit hydrogen venting for a short period of time following oxygen venting.

4) **LH2 Pulsed Chilldown:**

Prior to pumping LO2, the RL10 engines must be chilled. This is typically accomplished by flowing cryogenic propellants through the engine. Flight demonstrations conducted during the 1990's on Atlas and Titan Centaurs demonstrated that pulsing the LO2 flow significantly reduces the required quantity of propellant. Information gained from the 1990's demonstrations formed the basis of Centaur's current LO2 "trickle" chilldown process that substantially reduced the required LO2 consumption.

The demonstration performed on the DMSP-18 mission was designed to provide similar data for the LH2 pump chilldown. The long coast during which the settling demonstrations were performed allowed the Centaur feedlines and RL10 engine hardware to warm to relatively high temperatures. The LH2 flow was then pulsed multiple times prior to the second main engine start. Each pulse consisted of a period of liquid flow followed by a period of no flow to allow LH2 to boil and cool the pump. Flight results showed that the pulsed chilldown did a good job of removing heat from the feedline and pump housing while reducing propellant usage. This chilldown technique shows good promise for future long coast missions.

5) **GO2 Venting during Engine Burn:**

There are certain situations where it is advantageous to rapidly reduce Centaur LO2 tank pressure during the burn. The influence of this pressure change on RL10 operation and Centaur environment was demonstrated on this mission. Extra instrumentation was mounted on various Centaur aft bulkhead components to determine the vibration environment and validate that the oxygen vent plume did not create an adverse environment by interacting with the engine plume. Mission results show that no adverse environment was observed and RL10 engine operation was unaffected by the pressure change, thus demonstrating that venting of the oxygen tank is feasible for future missions.

6) **Modified Minimum Residual Shutdown (MRS):**

MRS allows Centaur to continue RL10 operation until liquid pull-through. Centaur utilizes MRS to maximize performance for missions where precise orbit injection accuracy is not required. Normal MRS logic commands RL10 shutdown as soon as acceleration starts to fall off. This demonstration allowed the RL10 to continue operation until thrust fell substantially.

Good data was obtained. Engine thrust decayed once the LO2 was depleted and vehicle acceleration dropped precipitously as expected. Following pull-through, the RL10 continued to generate thrust by burning a combination of liquid and gaseous propellants before the RL10 reached final shut down at a preset time. During this period, Centaur experienced a few thrust spikes possibly caused by ingestion of trapped liquid. Potential benefits of utilizing this two-phase engine operation for future missions include increased engine performance or improved Centaur disposal options.

Useful data has already been obtained from these demonstrations and on-going detailed analysis by the Air Force and ULA will quantify the potential benefits and impacts of implementing these techniques. Just as flight demonstrations in the past have led to the high capability of today's Centaur, the results of these demonstrations will further allow ULA to improve on second stage design and operation to guide development towards more advanced space-based cryogenic systems.

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