The Next-Generation Heavy-Lift Vehicle—
The Inaugural Flight of the EELV Delta IV Heavy

Michael D. Berglund*, Dan Marin†, and Mark Wilkins††
The Boeing Company, Huntington Beach, CA 92647

Abstract

On December 21, 2004, The Boeing Company Delta IV Heavy launch vehicle lifted off from Cape Canaveral Air Force Station, Florida, at 4:50 p.m. EST, on a demonstration launch for the Air Force's Evolved Expendable Launch Vehicle (EELV) program. Achieving its primary objectives, this breathtaking launch marked the inaugural flight of the Boeing Delta Heavy.

The Heavy launch vehicle represents the largest of the five vehicles of the Delta IV family. The family consists of the Delta IV Medium, three Delta IV Medium vehicles with solid strap-on rocket motors (Medium-Plus variants), and the Delta IV Heavy. The current Heavy configuration has the highest mass-to-orbit performance capability of any U.S. expendable launch vehicle currently in production.

All Delta IV vehicle configurations utilize a common booster core (CBC). The Heavy employs two additional CBCs, serving as liquid rocket boosters for added payload capability. The vehicle measures 71.7 m in height when fully stacked with a payload.

Integrating a new launch vehicle with new launch site ground systems poses many unique challenges. This paper summarizes the flight readiness process that led to the inaugural Heavy launch, including the wet dress rehearsals. This paper will also discuss the primary objectives as well as the flight observations.

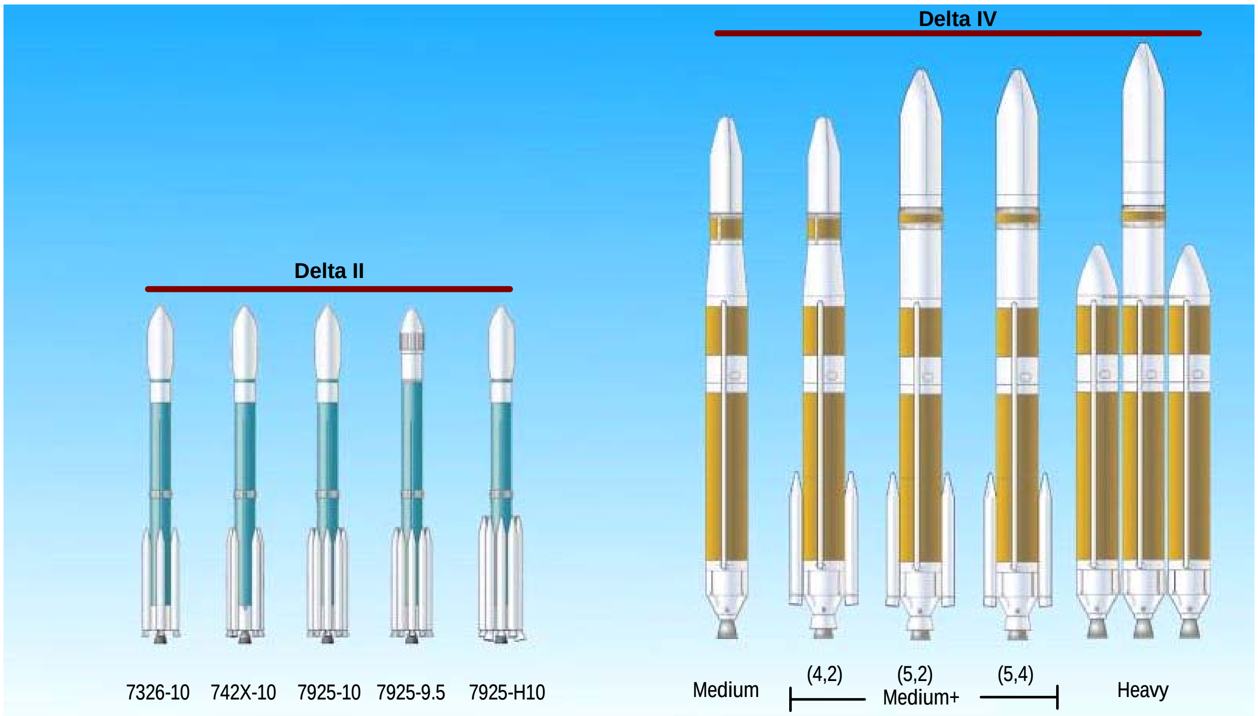
* Mission Integration Manager, Delta IV, 5301 Bolsa Ave., Huntington Beach, CA, MC H014-C462, AIAA Member
† Director, USAF EELV Program, 5301 Bolsa Ave., Huntington Beach, CA, MC H014-C416
†† Vice President, Delta Programs, 5301 Bolsa Ave., Huntington Beach, CA, MC H014-C415, AIAA Member

I. Introduction

The Delta Launch Vehicle Family

The Delta family of launch vehicles has continued to evolve throughout its 40-year legacy to meet customers' growing needs. The successful Delta IV development represents the most dramatic change in capability during this Delta legacy.

As shown in Fig. 1, Delta IV adds five vehicles to the Delta family: the Delta IV Medium, three Delta IV Medium vehicles with solid strap-on rocket motors (Medium-Plus variants), and the Delta IV Heavy with two strap-on common booster cores (CBC) serving as liquid rocket boosters.



		7326-10	742X-10	7925-10	7925-9.5	7925-H10	Medium	(4,2)	(5,2)	(5,4)	Heavy
GTO	(kg)	890	1,030	1,760	1,830	2,130	4,230	5,940	4,870	6,820	12,760
LEO	(kg)	2,470	2,880	4,600	4,780	5,650	9,110	12,300	10,620	13,870	21,890
GEO	(kg)						1,140	2,040	1,690	2,790	6,280

GTO = 185 x 35,786 km at 28.7 deg Delta II and 27.0 deg Delta IV. LEO = 407 km circular at 28.7 deg.
GEO = 35,786 km circular at 0 deg

5P247001

Figure 1. Family of Delta Launch Vehicles

The Delta IV family is built on a solid foundation of heritage hardware and proven processes in manufacturing, quality, engineering, and supplier management. The Delta IV family evolves to expand the Delta capability while at the same time creating a robust system with improvements in producibility and operability. The primary avionics system, the 4-m fairing, the 4-m cryogenic second-stage tanks, and the second-stage engine are examples of heritage hardware carried into the Delta IV design. In addition, the strap-on solid rocket motors are derived from the smaller diameter solids used on Delta II and Delta III.

All configurations of the Delta IV family share the same first stage, the common booster core. The CBC consists of the interstage, liquid oxygen (LO_2) tank, centerbody, liquid hydrogen (LH_2) tank, engine section, and the U.S.-developed Pratt & Whitney Rocketdyne RS-68 engine.

The RS-68 engine, clean and environmentally friendly, utilizes LO_2 and LH_2 propellants producing more than 2918 kN of thrust (sea level).

The Medium-Plus variants consist of a CBC and either two or four 1.5-m-diameter graphite-epoxy solid propellant strap-on motors. These motors are designed and manufactured by Alliant Techsystems and have both fixed and vectorable nozzle configurations. The Medium-Plus variants include either a 4- or 5-m-diameter fairing.

The second-stage Pratt & Whitney Rocketdyne RL10B-2 engine derives its power from LO_2 and LH_2 cryogenic propellants as well and is used on all Delta IV configurations. Producing 110 kN of thrust, the engine possesses an extendible nozzle designed for boost-phase environments and longer second-stage burn durations.

II. Heavy Launch Vehicle—First Flight

Vehicle Description

The first-flight Heavy launch vehicle configuration consisted of a 5-m-diameter composite payload fairing and the 5-m payload attach fitting assembly with the 1194-mm clampband (Fig. 2). The second stage consisted of a 5-m-diameter LH_2 tank and the RL10B-2 engine with an extendible nozzle. There are three CBCs—the starboard and the port strap-on boosters and the center core. The RS-68 engine powers each CBC.

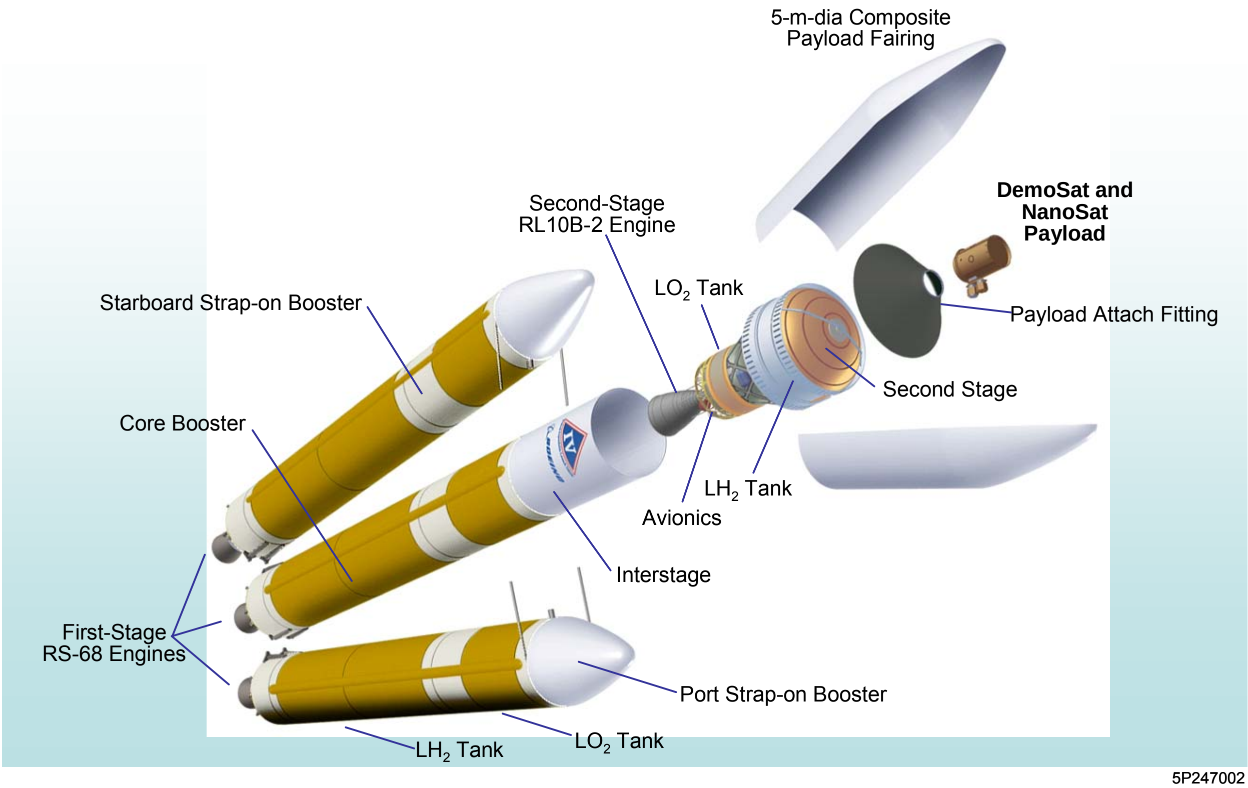


Figure 2. Heavy Demo Launch Vehicle Configuration

First-Flight Objectives

The Heavy launch vehicle configuration can deploy large payloads to geosynchronous transfer orbit (GTO), polar, Sun-synchronous, planetary/escape, and direct insert into geosynchronous Earth orbit (GEO).

The objectives of the first mission, designated as "Heavy Demo," included the demonstration of launch pad and Heavy vehicle integration, the new 5-m-diameter second stage and composite payload fairing, the heavy boost phase, and the heavy-lift capability to directly insert a demonstration satellite (DemoSat) into GEO. Achieving the latter objective required three burns of the RL10B-2 second-stage engine, with an overall mission duration of nearly 6 hours, including 5.2 hours of coast. See Fig. 3 for the planned Heavy Demo orbit profile.

Another objective was to collect environmental and performance data to validate systems qualification and analytical models. The DemoSat itself weighed approximately 6124 kg.

In addition to DemoSat, the Delta IV Heavy demonstration mission included an auxiliary payload, NanoSat-2, for the Department of Defense (DoD) Space Test Program (STP). The primary objectives of NanoSat-2 were to validate the integration of an auxiliary payload on a Delta IV and to demonstrate low-shock satellite separation systems for future government small-satellite missions.

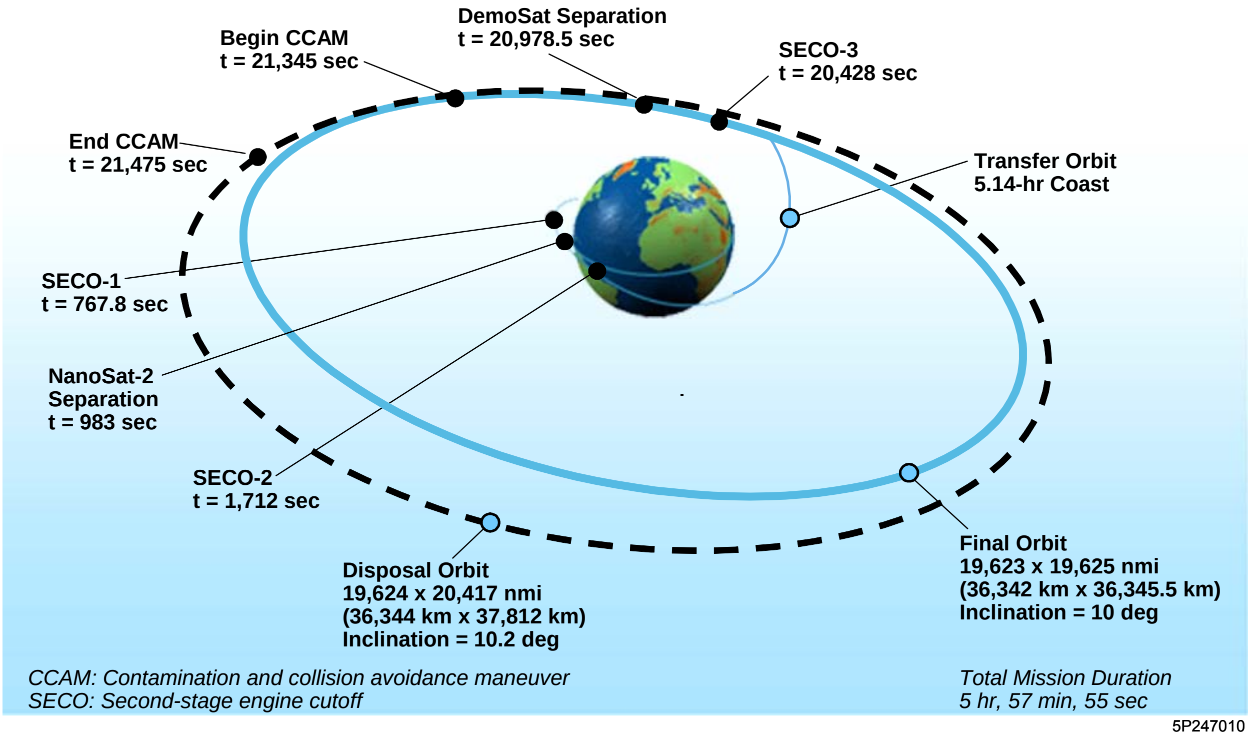


Figure 3. Delta IV Heavy Demo Orbit Planned Profile

III. Heavy Vehicle Processing

The first and second stages of the Heavy Demo mission completed mating operations in the Horizontal Integration Facility (HIF) on December 7, 2003. The Heavy vehicle then exited the HIF and rolled out to Space Launch Complex 37 at Cape Canaveral Air Force Station, Florida, on December 9. Modifications to the launch pad for the Heavy vehicle were completed, and the vehicle was erected on the launch pad (Fig. 4).

The electrical compatibility test was completed on February 2, 2004. This test verified the communications between the avionics boxes within the launch vehicle. Electromagnetic interference/electromagnetic compatibility (EMI/EMC) testing was completed on February 19. This test ensured that the Heavy vehicle was compatible with the Eastern Test Range electromechanical and radio frequency environment. The tests were conducted while the Mobile Service Tower (MST) was around the vehicle, as well as when rolled back.

On March 18, 2004, qualification testing was completed for the Heavy vehicle guidance and control systems. The DemoSat payload was mated to the payload attach fitting on April 13 at the Astrotech facility, using a clamp-band separation system (Fig. 5).

On April 20, 2004, the simulated flight test was completed. The purpose of this test was to check out vehicle hardware and software performance through the entire mission, from T–0 through the contamination and collision-avoidance maneuver, post-spacecraft separation.

In early July, the DemoSat encapsulation/fairing installation was completed. Figure 6 shows the fairing fully encapsulating the payload.

On July 24, 2004, the encapsulated DemoSat/Nanosat-2 payload was transported to the launch pad, hoisted by crane in the MST, and mated to the second stage.

On November 19, 2004, the vehicle flight program verification (FPV) was performed. It is similar to the simulated flight test, with the exception that the FPV uses actual vehicle software configured for the mission as opposed to test software.

All of these test activities played a vital role in the flight readiness process in preparation for a successful flight. To further enhance the flight readiness process before the simulated flight test occurred, a series of propellant-loading tests began.

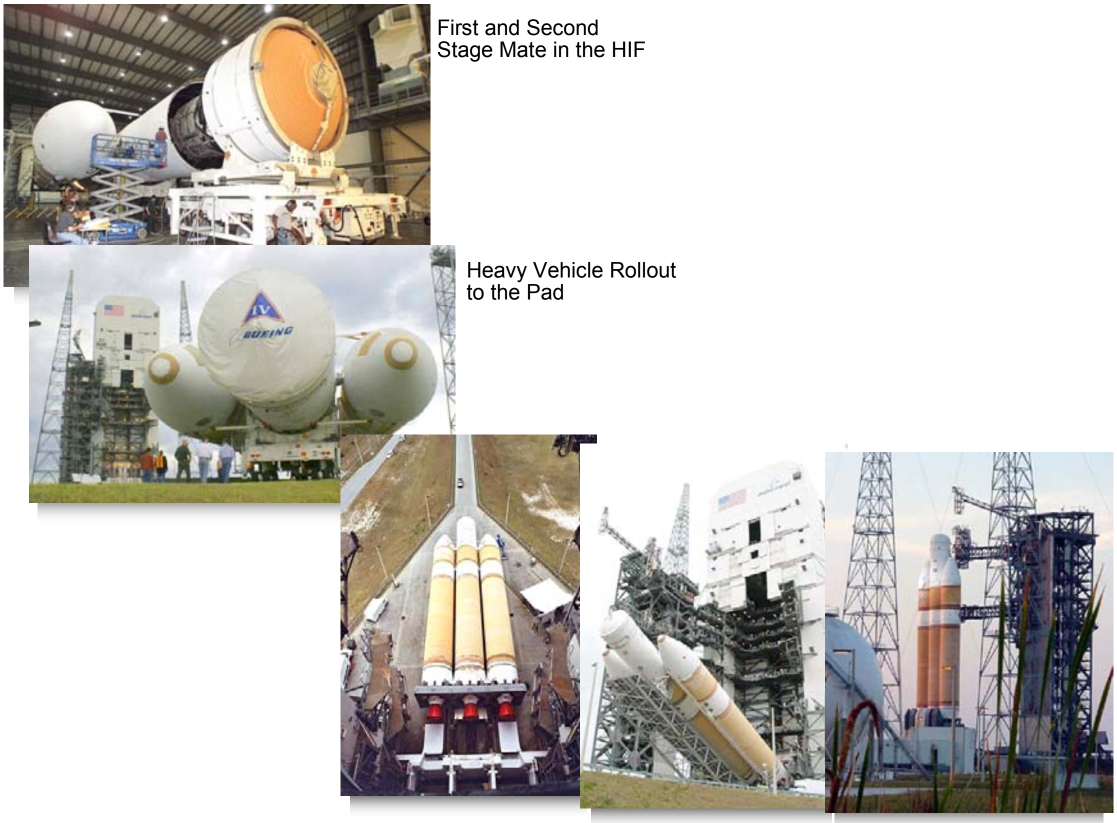


Figure 4. Heavy Demo Vehicle Processing

Figure 5. DemoSat and NanoSat-2 Mate to the Payload Attach Fitting

Figure 6. Payload Encapsulation

IV. Heavy Demo Propellant-Loading Test Series

To demonstrate the physical and functional integrity and integration of the launch vehicle (LV), Launch Complex 37 at Cape Canaveral Air Force Station, and the Launch Control Center (LCC) systems under prelaunch and postabort conditions, a variety of tanking tests were planned for the Heavy Demo vehicle. Specifically, two cryogenic propellant-loading tests, along with two wet dress rehearsals, were scheduled. The standard countdown timeline was used as a model for the tanking tests and the wet dress rehearsals.

On October 27, the final test in the propellant-loading test series, wet dress rehearsal No. 2, was performed (Fig. 7). The test series was successful, and the primary objectives were achieved, including the verification of the sequence of events of the terminal countdown, the launch pad modifications for the Heavy vehicle, and the T–5 minute count with the turbine pump assembly spin-up in preparation for engine ignition.


5P247006

Figure 7. Wet Dress Rehearsal No. 2

Achieving the objectives of the propellant-loading test series played a vital role in the successful inaugural launch of the Delta IV Heavy launch vehicle.

V. Flight Readiness Review Process

In addition to propellant-loading tests, the inaugural Delta IV Heavy launch vehicle was subjected to a rigorous review process to ensure mission success. The Delta IV flight readiness review process was derived from the flight-proven Delta II and Titan IV payload faring launch readiness review process.

This disciplined process integrates functions from quality assurance, manufacturing, launch site processing, and engineering. The process consists of a series of reviews scheduled to validate and establish, with a high degree of confidence, that the launch vehicle and ground support equipment will perform reliably and meet mission objectives.

The Air Force and its independent assessment teams were engaged with Boeing in these reviews from the start. They made valuable contributions to the flight readiness process, which helped reinforce the strong partnership between the Boeing Delta team and the Air Force. The chronology of the flight readiness reviews for the Heavy vehicle is shown in Fig. 8.

Heavy Demo Postflight Data Critique

A postflight data critique, an essential part of the launch readiness review process, was held on January 25–26, 2005. This review evaluated mission performance based on available flight telemetry data. Appropriate technologies provided an analysis of vehicle and payload performance to predefined performance criteria and attainment of mission objectives.

One anomaly and multiple observations were documented. The Heavy Demo flight observations and closure plans were managed per the launch assurance process (Boeing procedures 2.3.1 and 3.1.3.11) and tracked to closure on the Delta Action Item Database (AIDB).

VI. Heavy Demo—Launch

On December 21, 2004, at 4:50 p.m. EST, in a spectacular display of cryogenic propellant combustion, the Delta IV Heavy lifted off from Space Launch Complex 37 at Cape Canaveral Air Force Station (Fig. 9).

The launch opened a new era in heavy-lift capability for the U.S. space program and marked the first heavy-lift launch for the Air Force's Evolved Expendable Launch Vehicle (EELV) program.

Following the 5-hr and 50-minute flight, the DemoSat payload was successfully separated, although in a lower-than-expected orbit. This in-flight anomaly will be discussed more in detail below.

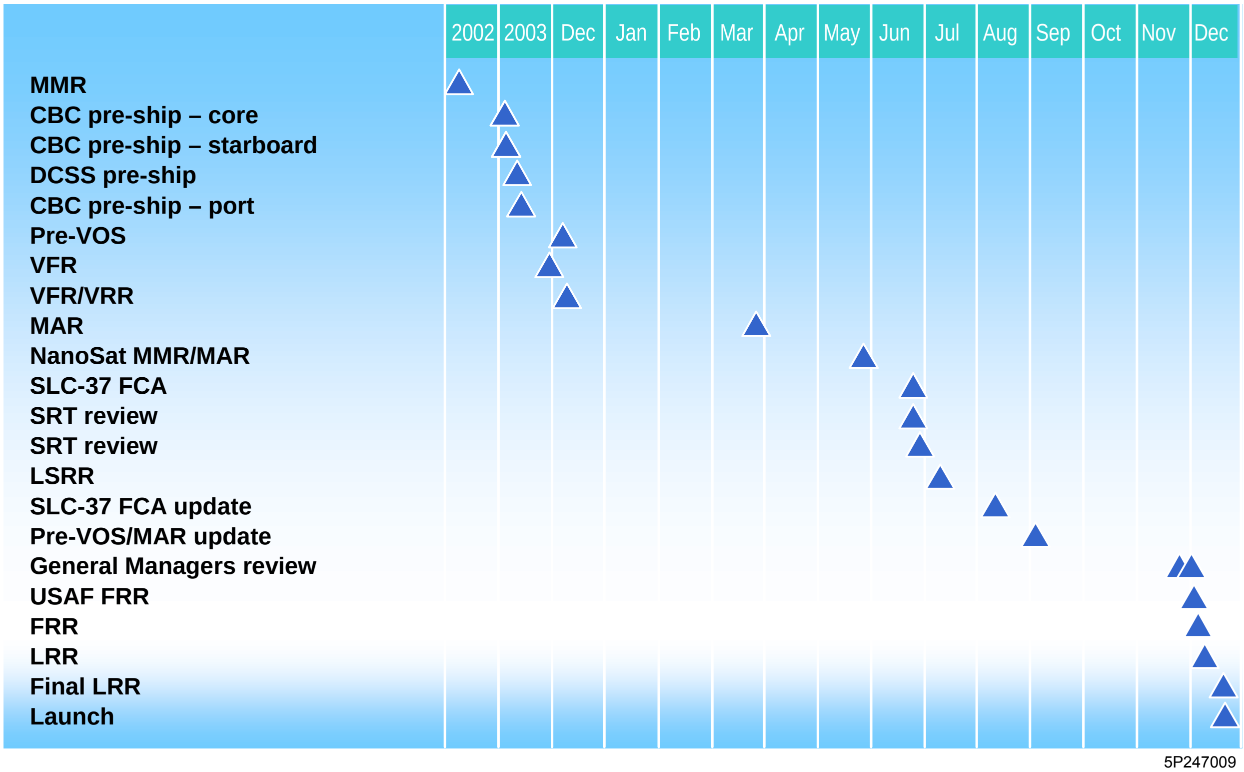


Figure 8. Chronology of the Flight Readiness Reviews

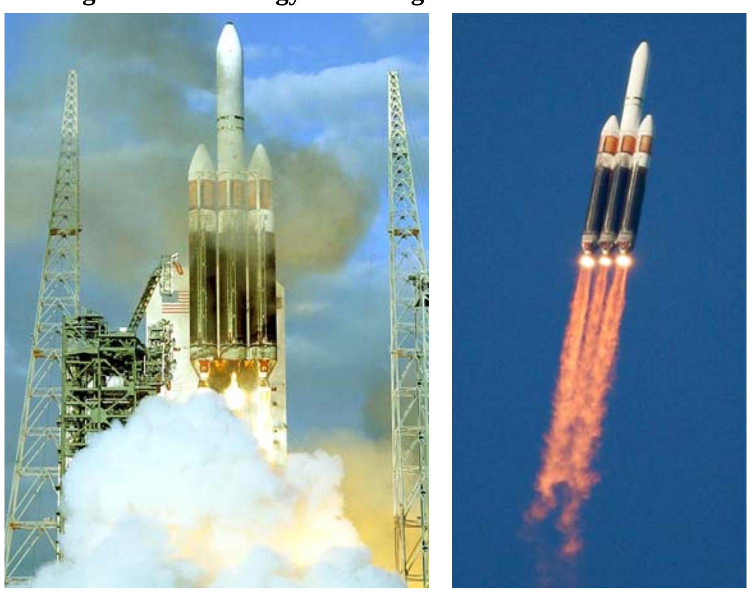


Figure 9. Heavy Demo Liftoff

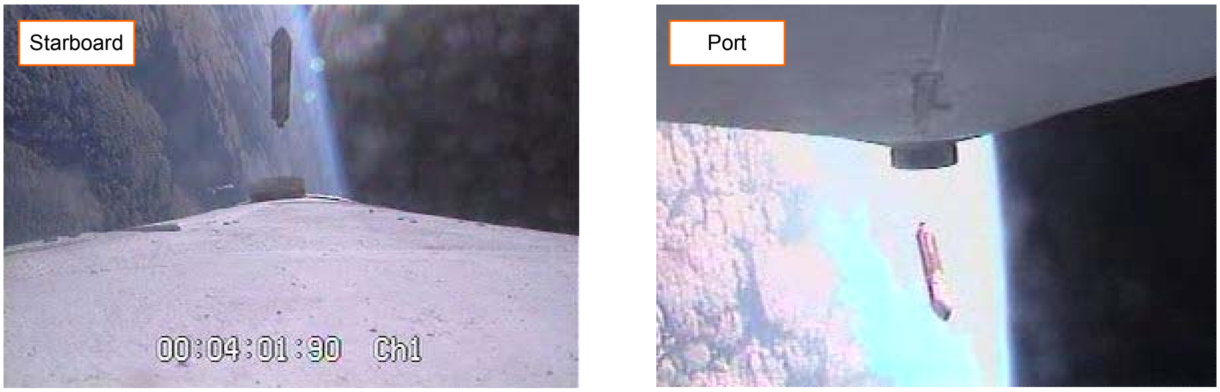
VII. Heavy Demo—Accomplishments

The primary objectives of the demonstration flight of the new Heavy vehicle were accomplished. They included demonstration of:

- Heavy boost phase, including three liquid boosters (Fig. 10 shows the starboard and port CBCs shortly after jettison)
- New 5-m-diameter second stage and composite payload fairing
- Extended coast and second-stage third burn
- Direct geosynchronous injection (Fig. 11 shows the DemoSat payload separation event)

- Delta IV secondary payload integration and separation
- Activation and usage of SLC-37 for a Heavy launch

In addition, a wealth of environmental and performance data were collected. The flight instrumentation included over 1000 sensors. The instrumentation was placed on the CBCs, second stage, payload attach fitting, and the fairing and included microphones, accelerometers, thermal sensors, pressure transducers, speed sensors, position sensors, calorimeters, strain gauges, and radiometers. Five cameras were included to provide in-flight video. Figure 12 shows, for example, the payload attach fitting/spacecraft interface accelerometer and its location on the vehicle.



5P247008

Figure 10. Starboard and Port CBC Jettison

5P247011

Figure 11. DemoSat Payload Separation

Nonflight instrumentation was also utilized and strategically placed to gather valuable data to quantify dynamic environments at hydrogen ignition and liftoff.

The plethora of data proved invaluable in postflight reconstruction, anomaly resolution, analytical model validation, and system qualification validation.

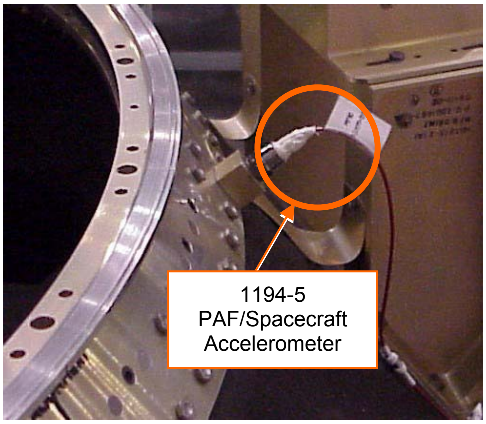
VIII. Earlier-Than-Expected Main Engine Cutoff (MECO) Anomaly

During flight, both the strap-on CBC MECO and the core CBC MECO were initiated by the LO_2 depletion sensors. The port, starboard, and core CBC boosters experienced MECO approximately 6 seconds prior to planned events. This required a longer-than-expected second-stage first burn to compensate. During the third and final burn, the supply of LO_2 was depleted and the payload separated before the final orbit could be reached.

An anomaly investigation was initiated following the launch. Established procedures outlined the anomaly investigation process and determined the documentation tools to be used, the approval authority, the final report requirements, and any launch constraint rules.

The Air Force-led team, consisting of Boeing, the Aerospace Corporation, as well as other independent assessment teams, together investigated this anomaly and determined root cause and corrective action. A formal anomaly report was published that documents all the details and analysis that led to root cause determination and final closeout of this anomaly.

The root cause was identified as a fluid cavitation within the LO_2 feed system. The cavitation was induced by flow restrictions in the feedline itself. The cavitation effect, or vapor pocket, extended to the location of the engine cutoff (ECO) sensors and triggered them to shut off the engines.



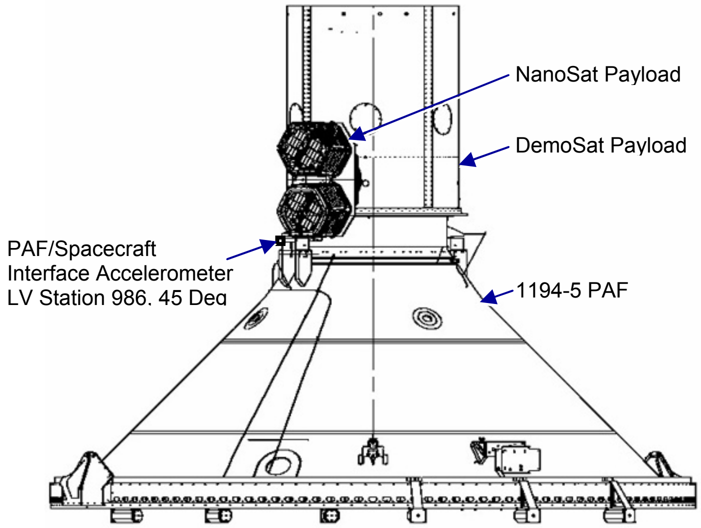


Figure 12. Payload Attach Fitting Interface Accelerometer

To eliminate the formation of cavitation under flight conditions similar to the Heavy Demo, corrective action steps have been implemented. The primary solution was to increase the pressure in the LO_2 propellant tank sufficiently enough to offset the pressure restrictions within the LO_2 feedline.

Using the knowledge gained during the Heavy Demo flight, the potential for cavitation is now checked for every Delta IV mission, under nominal and worst-case predicted flight conditions.

IX. Conclusion

The propellant-loading test series, the flight readiness review process, and contributions from key partners such as the Air Force and the Aerospace Corporation led to a successful inaugural flight of the Delta IV Heavy launch vehicle. This launch represented a remarkable American technological achievement. It demonstrated the next-generation heavy-lift vehicle and is currently America's singular option of a ready heavy-lift capability.