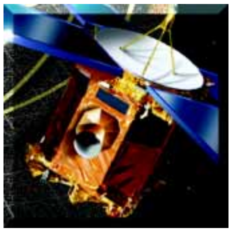


Design, Development, and Flight of the NEAR Propulsion System

Larry E. Mosher and Sam Wiley

Mission velocity change requirements for the Near Earth Asteroid Rendezvous (NEAR) mission dictated the use of regulated dual-mode propulsion and a lightweight, stiff composite structure. Fixed solar array and high-gain antenna locations, combined with mission trajectory constraints, dictated an unusual thruster arrangement. A unique sequencing of individual tank outlet latch valves will maintain the spacecraft y and z center of mass within ±2 mm during expulsion of the 315-kg propellant load. The use of flight-proven components, a sequential protoflight test philosophy, and a small integrated product team resulted in the successful development, manufacture, testing, and integration of the propulsion system into the spacecraft in just 16 months. In-flight performance to date has been very close to pre-flight predictions.

(Keywords: Bipropellant, NEAR propulsion system, Regulated pressurization.)

INTRODUCTION

Spacecraft Description

The Near Earth Asteroid Rendezvous (NEAR) spacecraft was designed with a separate propulsion module to simplify the propulsion system-to-spacecraft interfaces and greatly reduce schedule risk. The core propulsion system is located inside the main spacecraft structure (see Fig. 1) attached to the aft deck. Six fine velocity control (FVC) modules are located on the aft and forward decks, and the large velocity adjust (LVA) thruster and its heat shield protrude through the center of a side panel, aligned to the spacecraft center of mass. Solar panels and the high-gain antennas dominate the forward deck. The spacecraft science instruments are mounted on the far bottom side of the aft deck facing

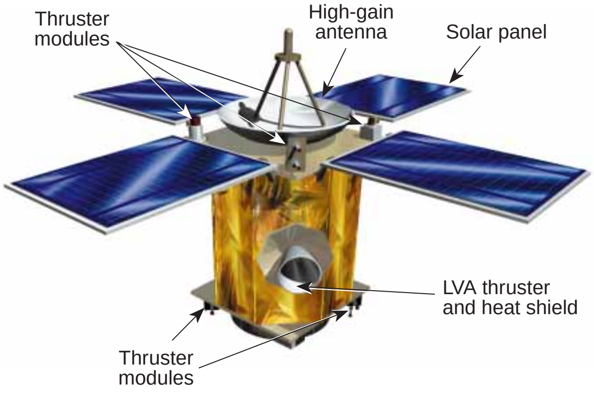


Figure 1. NEAR spacecraft flight configuration.

180° away from the LVA thruster. The remainder of the spacecraft subsystems are mounted on the inside of the fore and aft decks.

Mission Requirements

A detailed chronological breakdown of the planned burns of the propulsion system during the mission and their resulting propellant requirements are given in Table 1. The mission specification requires the propulsion system to deliver sufficient impulse to provide 1175-m/s velocity change (ΔV) capability in bipropellant mode and the equivalent of 245-m/s ΔV capability in monopropellant mode to an 805-kg beginning-of-life spacecraft. The table shows that these values are expected to be exceeded. The first six entries in the table reflect actual separation detumble, the first momentum dump, and the first four trajectory correction maneuvers (TCMs).

Propulsion System Requirements

The specified NEAR mission profile had to be satisfied by the propulsion system within the specific impulse, oxidizer-to-fuel mixture ratio, wet and dry mass, and established capacity constraints.

The propulsion system, in response to commands from the attitude control system, provides large or small ΔV maneuvers, attitude control during large or small ΔV maneuvers, and spacecraft momentum

Table 1. NEAR mission profile.

Date	Event	ΔV (m/s)	Impulse (ns)	I_{sp} (s)	Propellant mass (kg)
2/16/96	Stabilization	0.16	127.71	228.48	0.06
2/24/96	Momentum dump	0.11	92.50	229.00	0.04
3/2/96	TCM-1	9.74	—	234.98	3.39
9/6/96	TCM-2A	2.13	—	228.48	0.74
9/6/96	TCM-2B	0.16	—	228.48	0.06
1/6/97	TCM-3	0.06	—	228.48	0.02
1/29/97	TCM-4	0.11	—	228.48	0.04
5/21/97	TCM-5	0.66	—	220.00	0.25
6/20–26/97	TCM-6&7	0.00	—	220.00	0.00
7/3/97	Settle	2.88	2302.00	234.98	1.00
7/3/97	TCM-8[a]	264.59	—	313.55	65.92
7/3/97	Attitude control	1.59	—	220.00	0.59
7/17/97	TCM-9	5.53	—	234.98	1.76
7/17/97	Attitude control	1.00	—	220.00	0.34
1/22/98	TCM-10	10.00	—	234.98	3.16
1/22/98	Attitude control	1.00	—	220.00	0.34
12/20/98	Settle	3.16	2302.00	234.98	1.00
12/20/98	Rendezvous burn 1	619.55	—	313.55	132.55
12/20/98	Attitude control	3.72	—	220.00	1.25
12/27/98	Settle	3.88	2302.00	234.98	1.00
12/27/98	Rendezvous burn 2	294.35	—	313.55	54.00
12/27/98	Attitude control	1.77	—	220.00	0.48
12/27/98	Rendezvous burn 3	40.00	—	234.98	9.24
12/27/98	Attitude control	0.24	—	220.00	0.06
1/3/99	Rendezvous burn 4	5.00	—	234.98	1.14
1/3/99	Attitude control	0.50	—	220.00	0.12
1/10/99	Eros flyby[b]	—	—	—	—
1/12/99–2/6/00	Eros operations	66.00	—	228.48	15.28
	N_2H_4 ΔV reserve	117.01	—	234.98	25.31
	Total ΔV	1454.89			
			Total usable propellant		319.15

Note: TCM = trajectory correction maneuver, ΔV = velocity change, I_{sp} = specific impulse, dashes in Impulse column = not applicable.

[a]Deep space maneuver.

[b]Dashes for Eros flyby = no activity.

management. The remaining system requirements are as follows:

- Package propulsion system to fit within the NEAR spacecraft envelope.
- Restrict fluid load to 319.7 kg, including He and residual propellant.
- Use flight-proven components.
- Use components that will last for the mission duration of 4 years.
- Locate center of mass (wet) as follows: x,y within 10 mm and z within 5 mm of the target given in the interface control document.[1]
- Restrict center-of-mass travel to ± 20 mm during propellant expulsion.
- Maintain core propulsion system temperature within range of 7 to 55°C while in a −30 to +55°C environment.
- Maintain FVC thruster module temperature within range of 7 to 55°C while in a −273 to +55°C environment.
- Provide minimum ΔV bit of 10 mm/s and minimum impulse bit of 0.2 N·s.

Safety factors (such as burst pressure and maximum expected operating pressure) that were required to be met by the system are as follows: tanks, 2.0; components, 2.5; and lines, 4.0. All designs for the flight system and ground support equipment had to satisfy the launch site safety document,[2] the pressure vessel design document,[3] and McDonnell Douglas launch vehicle requirements.

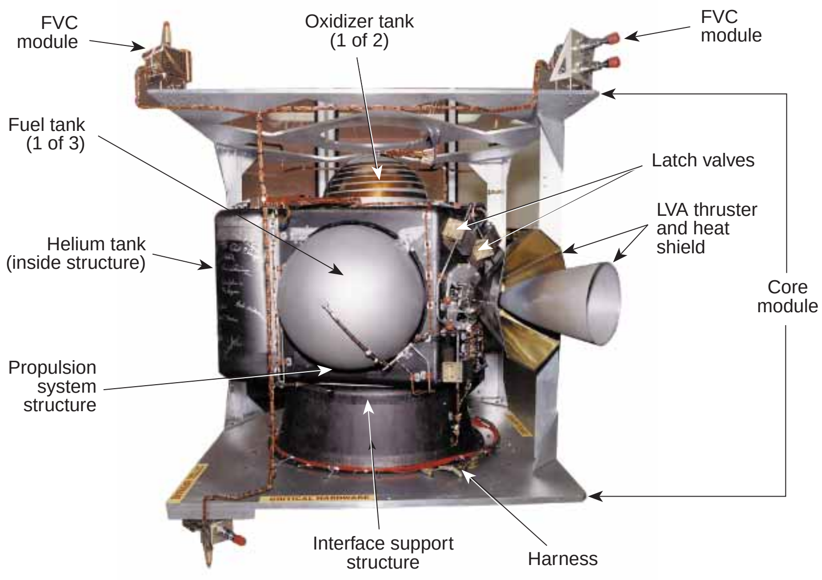


Figure 2. NEAR propulsion system configuration.

DISCUSSION

Propulsion System Configuration and Design

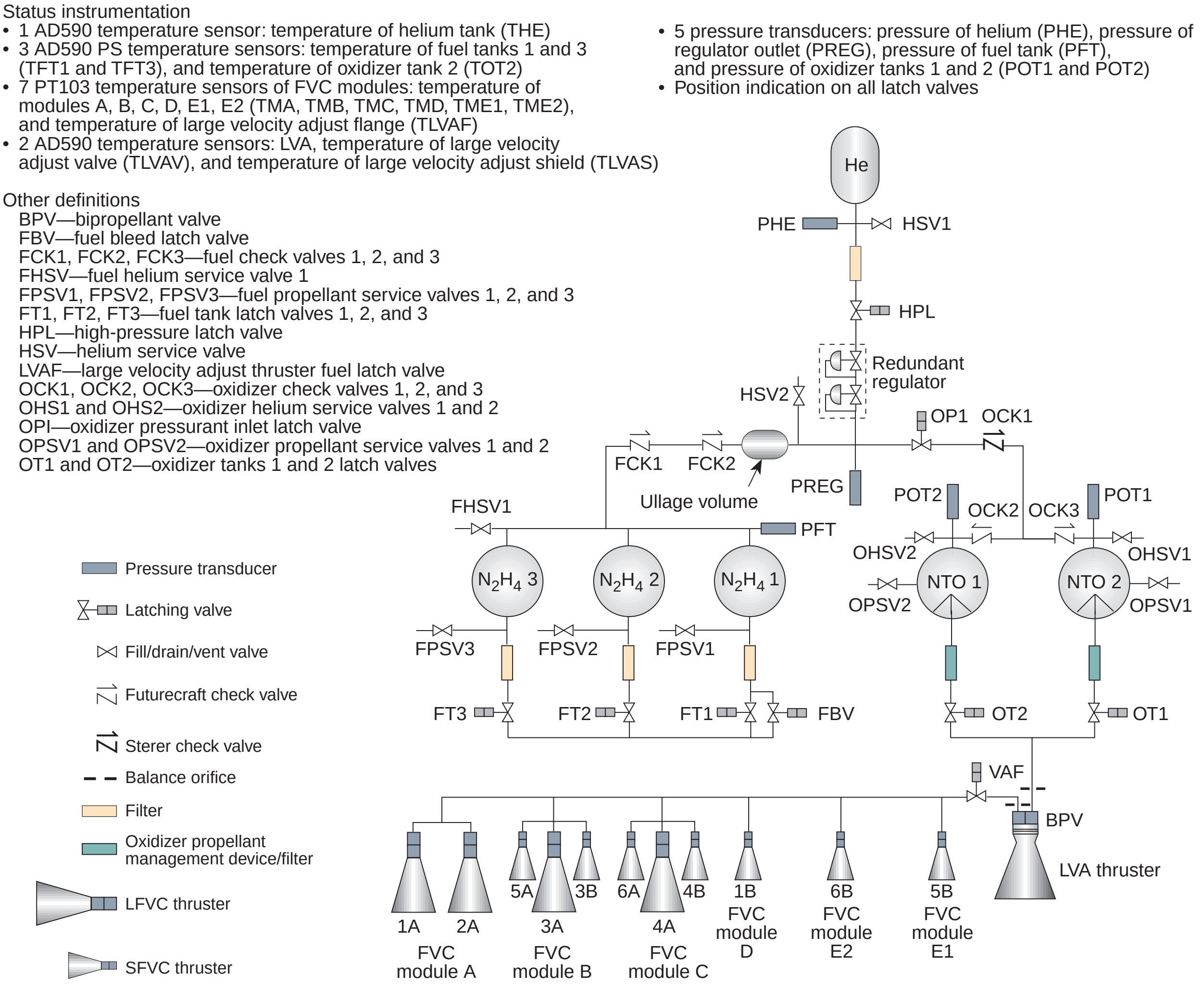
The propulsion system, shown literally in Fig. 2 and schematically in Fig. 3, is made up of two major elements: the core module and the FVC thruster modules. The core module supports the propellant and pressurant tanks, up to 346 kg of fluids, all fluid components and their interconnecting manifolds, the bipropellant thruster and its heat shield, and the electrical harness.

The core propulsion system contains two oxidizer tanks, three fuel tanks, a helium tank located inside the propulsion system structure (PSS), one flat structure section (the valve panel) containing most of the required system control components, and a second flat section that supports the 470-N dual-mode nitrogen tetroxide (N_2O_4)–hydrazine (N_2H_4) bipropellant thruster and heat shield. The LVA heat shield is used to protect the interior of the spacecraft from LVA thruster radiation.

The tanks and fluid components are connected using either 0.95-cm or 0.635-cm 3 Al–2.5-V titanium tubing, with a 0.071-mm wall. The system manifolds are completely welded. All 12 system thrusters have stainless steel inlet lines and are connected to their respective titanium manifolds with inertially welded bimetallic tube joints. All system welds underwent X-ray, dye penetration, and proof and leak inspections.

Four 21-N N_2H_4-monopropellant large FVC thrusters and seven 3.5-N N_2H_4-monopropellant small FVC thrusters are arranged in six FVC thruster modules (modules A, B, C, D, E1, and E2) mounted to the fore and aft spacecraft decks. A typical module consists of a one-piece machined 6061-T6 aluminum housing, thruster-to-housing titanium spacers, housing-to-spacecraft titanium standoffs, stainless steel fasteners, valve inductive load-suppression diodes, Deutsch terminal blocks (used for electrical connections), and the module harness. Each FVC thruster module was independently manufactured and acceptance tested before installation on the top-level system.

FVC thruster locations for the propulsion system are established to redundantly provide torque around all axes with A- and B-side sets of thrusters, as shown in Fig. 4. The ΔV forces in the $\pm x$ and the $\pm z$ direction are also provided by the FVC thrusters, with the $+x$ FVC thrusters providing some LVA redundancy and a 10-mm/s ΔV trim capability. The minimum ΔV increment of 10 mm/s is achievable in all available ΔV directions. An attitude control system impulse bit of 0.2 N·s for momentum unloading is achievable with the B-side thrusters, but is not achievable in all



Status instrumentation

- 1 AD590 temperature sensor: temperature of helium tank (THE)
- 3 AD590 PS temperature sensors: temperature of fuel tanks 1 and 3 (TFT1 and TFT3), and temperature of oxidizer tank 2 (TOT2)
- 7 PT103 temperature sensors of FVC modules: temperature of modules A, B, C, D, E1, E2 (TMA, TMB, TMC, TMD, TME1, TME2), and temperature of large velocity adjust flange (TLVAF)
- 2 AD590 temperature sensors: LVA, temperature of large velocity adjust valve (TLVAV), and temperature of large velocity adjust shield (TLVAS)
- 5 pressure transducers: pressure of helium (PHE), pressure of regulator outlet (PREG), pressure of fuel tank (PFT), and pressure of oxidizer tanks 1 and 2 (POT1 and POT2)
- Position indication on all latch valves

Other definitions

BPV—bipropellant valve
FBV—fuel bleed latch valve
FCK1, FCK2, FCK3—fuel check valves 1, 2, and 3
FHSV—fuel helium service valve 1
FPSV1, FPSV2, FPSV3—fuel propellant service valves 1, 2, and 3
FT1, FT2, FT3—fuel tank latch valves 1, 2, and 3
HPL—high-pressure latch valve
HSV—helium service valve
LVAF—large velocity adjust thruster fuel latch valve
OCK1, OCK2, OCK3—oxidizer check valves 1, 2, and 3
OHS1 and OHS2—oxidizer helium service valves 1 and 2
OPI—oxidizer pressurant inlet latch valve
OPSV1 and OPSV2—oxidizer propellant service valves 1 and 2
OT1 and OT2—oxidizer tanks 1 and 2 latch valves

Figure 3. NEAR propulsion system schematic.

directions for the A-side thrusters. The worst-case A-side impulse bit is 0.7 N·s.

Propellant is contained in two 16.3-atm, 60-L oxidizer tanks located on the launch vehicle spin axis and three 16.3-atm, 91-L fuel tanks located radially along the LVA thruster plane, 120° apart. This configuration was selected to allow for system balance and stability, both during the third-stage burn of the Delta launch vehicle and during LVA thruster firing. The oxidizer tanks use settling forces and in-line propellant management devices for delivery of gas-free propellant, while the fuel tanks use elastomeric diaphragms for positive gas-free expulsion. The propellant tanks are filled and pressurized through individual tank fill and drain valves. Center-of-mass control is achieved by sequentially opening and closing the appropriate individual propellant tank outlet latch valves.

Pressurization is achieved by a common regulated helium system consisting of a 211-atm, 43.4-L helium tank, a high-pressure latching valve, and a series-redundant regulator. The remaining latch valves and check valves separate the hydrazine and the N_2O_4.

System status is provided by position indicators on each latch valve and by one 340-atm helium tank pressure transducer, one 34-atm regulator outlet transducer, and three 34-atm propellant tank pressure transducers. Status is also provided by temperature sensors located on fuel tanks 1 and 3; oxidizer tank 2; the helium tank; the LVA flange, valve, and radiation shield; the propellant manifolds in FVC thruster modules A, B, and C; the thruster valve in module D; and the aluminum housings in modules E1 and E2.

Redundancy is provided in selected mission-critical locations. No single-point failures exist throughout the wiring, connections, heaters, and thermostats. The fuel-side Futurecraft check valves are series redundant and internally parallel redundant; the regulator is series redundant; several latch valves have redundant coils; and all monopropellant thrusters have series-redundant valves.

	A-side thruster group	B-side thruster group
Torques		
+ Around x' (R)	5A	6B
− Around x' (R)	6A	5B
+ Around y' (P)	1A and/or 2A	3B + 4B
− Around y' (P)	3A + 4A	1B
+ Around z' (Y)	4A + (1A or 2A)	3B + 1B
− Around z' (Y)	3A + (1A or 2A)	4B + 1B
Forces		
$+x'$	LVA or 1A+2A+3A+4A	—
$-x'$	—	1B + 50% (3B + 4B)
$+y'$	—	—
$-y'$	—	—
$+z'$	5A + 6A	—
$-z'$	—	5B + 6B

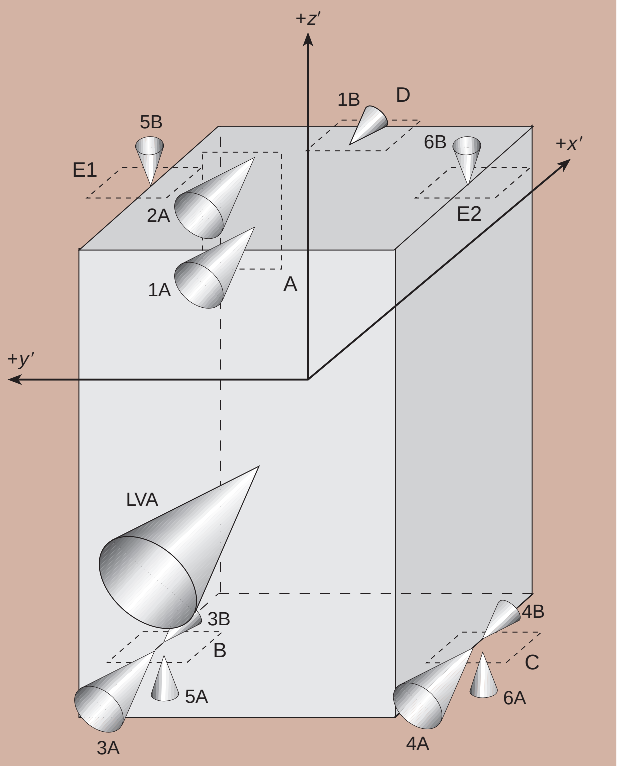


Figure 4. NEAR thruster definitions and locations. The torque and force matrix is shown at the top.

Thermal Design

Propulsion system thermal control is accomplished using multilayer insulation (MLI) blankets, redundant heaters, thermal isolation standoffs, thermal coatings, copper wire heat shunts, and heat shields.

All heaters, except the FVC thruster catbed heaters, are controlled by thermal switches. The catbed heaters are on/off controlled by the spacecraft. Thermal switch ranges are approximately 20–30°C for the primary heaters and 10–19°C for the secondary heaters.

All the system blankets are constructed of a 0.075-mm Kapton outer layer (except the FVC manifold blankets that use 0.025-mm aluminized-Mylar outer layers) and 0.0064-mm aluminized-Mylar inner layers, all separated by Dacron netting. Fifteen layers were used in each blanket. Blankets were installed using a combination of Velcro and Kapton tape. Each blanket is grounded either to the propulsion system or the spacecraft.

Core module heat is provided by fuel, oxidizer and helium tank heaters, a regulator outlet ullage volume heater, lower oxidizer line and propellant management device heaters, the structure heater, and the pressure transducers. The core module is covered by a five-segment MLI blanket. All five propellant tanks and the helium tank have primary and secondary thermal switch-controlled heaters.

The LVA has both mounting flange and valve primary and secondary heaters to maintain the valve and injector temperatures above the required minima. An LVA heat shield is used to attenuate the thruster firing heat flux that would otherwise overheat components inside the spacecraft. LVA testing showed that the external flux attenuation of the shield will keep spacecraft internal component temperatures below 50°C for the longest planned LVA burn of 16 min.

The FVC manifold heaters are separated into eight control zones, each longitudinally sheathed in No. 18 average wire gage copper wire, spiral wrapped with heaters and overwrapped with a thermal blanket. The copper wire was used to help distribute heat longitudinally along the manifold length and to account for variations in blanket effectiveness. In addition, heater watt density was varied depending on the manifold's view of the inside of the spacecraft or deep space.

FVC thruster thermal control is provided by valve heaters, titanium thermal standoffs between the thruster flange and module housings, titanium thermal standoffs between the module housing and spacecraft deck, and module MLI blankets.

Electrical Design

Redundant power and telemetry wiring runs from each of the propulsion system components to eight interface connectors. Surge-suppression diodes are included in all thruster and latch-valve circuits. Resistor isolation is provided for the redundant pressure transducer output signals.

Electrical busing and internal propulsion system connections were made using Deutsch connector blocks.

Structural Design

A unique, mission-enabling stiff and lightweight composite structure was designed using a single, circular interface for the core propulsion module that aligns with the spacecraft interface to the launch vehicle adapter.

The structure includes the PSS, the interface support structure (ISS), and a secondary structure consisting of fill/drain valve brackets and latch valve brackets. The PSS and ISS weigh a total of only 32.2 kg and support up to 450 kg of inert propulsion system mass and propellant.

The ISS provides two functions: It supports the PSS and provides the proper dynamic isolation, and it provides for thermal isolation between the spacecraft deck (as cold as −30°C) and the PSS (temperature at +20°C). The ISS was constructed by hand laying a combination of two different unidirectional Hexcel prepregs over an aluminum male tooling mold. This one-piece structure incorporated composite flanges as mating interfaces with the aft deck of the spacecraft and the aft portion of the PSS. After layup, the ISS was vacuum bagged and cured.

The PSS was fabricated in one piece by first laying up prepreg on the inside of female tooling. This defined the exterior PSS surface. Female tooling was selected for the PSS to accurately control the propellant tank locations and hydraulic component mounting locations. Tank locations have a major influence on the propulsion system center of mass. Machined aluminum honeycomb sections separated by a layer of glass scrim cloth were then placed on the outer composite layer using a combination of film and foaming film adhesive. Tank mounting inserts and PSS-to-ISS interface spools were then placed in their appropriate locations and packed with foaming film adhesive. Next, an interior layer of composite was installed over the inner surface of the honeycomb. The entire PSS was then vacuum bagged and baked.

The result is a tightly, dimensionally controlled monocoque hexagonal structure with integral tank mounting inserts. Drill templates were used to machine mounting locations for tanks, latching valves, and most hydraulic components.

Following completion of both the ISS and PSS, adhesive shims were matched-machined to provide for proper dimensional control between the ISS-to-spacecraft interface and LVA thruster mounting location. The ISS and PSS were then bonded with adhesive and bolted together using 18 high-strength titanium bolts.

The secondary structure includes thruster module housings, an LVA thruster mounting bracket, and component mounting brackets. The FVC thrusters are mounted in single-piece machined-aluminum housings. The LVA thruster is secured to a tuned aluminum mounting plate. This plate was designed to attenuate high-frequency energy that could possibly damage the LVA thruster valve. Two composite brackets support the service valves. The LVA, helium tank, and oxidizer latch-valve mounting brackets are also single-piece machined from aluminum.

System Mass and Power

The propulsion system has a dry mass of 118 kg and a maximum cruise-mode power of 76 W (without the LVA flange heater on). Tables 2 and 3 summarize the final measured values of system mass and power.

PROTOQUAL TESTING PROGRAM

Protoqual testing (qualification-level testing of the flight article) of the NEAR propulsion system components, subassemblies, and system was completed using qualification by similarity and analysis, when possible, and testing at the vendor level, subassembly level, and assembly level, when not possible. All propulsion system testing was accomplished using the NEAR electronic ground support equipment (EGSE) that emulates spacecraft command and control. This equipment was built using commercially available hardware and used a personal-computer-based, Aerojet-developed, point-and-click software program.

Component-Level Testing

Where possible, existing qualification data on individual system components were used, allowing only

Table 2. NEAR mass summary.

Item	Mass (kg)
Major assemblies	
Structure	33.1
Helium tank assembly	10.1
Oxygen tank assembly	11.9
Fuel tank assembly	23.4
LVA assembly	9.9
FVC modules	10.3
Valves, electrical, thermal	19.3
Total dry mass	118.0
Helium	1.6
Usable N_2O_4/N_2H_4	315.1
Residual propellant	3.0
Total wet mass	437.7

Table 3. NEAR power summary.

Item	Power (W)
Valves	
3.5-N small FVC thruster	10.8
20.9-N large FVC thruster	35.1
467-N LVA thruster	15.7
High-pressure latch valve	42.7
3/8" latch valves	34.6
1/4" latch valves	16.6
Power buses	
Primary tank heaters*	27.2
Primary valve and line heaters*	44.6
LVA flange primary heater	12.5
LVA flange secondary heater	12.5
Secondary tank, valve, and line heaters	71.8
A-catbed primary heaters	23.0
A-catbed secondary heaters	22.8
B-catbed primary and secondary heaters	26.3
Pressure transducers*	4.0
*Total cruise mode power	75.8

Table 4. Component protoqual tests.

Component	Protoqual method
LVA thruster	Hot fire and sine and random vibration
LVA heat shield	Hot fire and sine and random vibration
FVC thrusters	Hot fire and sine and random vibration
Structure	Sine and random vibration
Helium tank	Analysis, proof, and leak test
Fuel, oxidizer tanks	Analysis, proof, and leak test
Latch valves	Sine and random vibration, proof, and leak test
Regulator	Sine and random vibration, proof, and leak test
Check valves	Sine and random vibration, proof, and leak test
Fill/drain valves	Analysis, proof, and leak test
Filters, propellant management device	Analysis, proof, and leak test
Pressure transducers	Sine and random vibration and burn-in

acceptance-level testing at the vendor. Existing qualified environments were compared to the NEAR environments for compatibility. Where discrepancies occurred, additional analyses or tests were conducted to verify acceptance. Completed component-level protoqual testing is outlined in Table 4.

FVC Thruster Module Testing

Each FVC thruster module subassembly underwent electrical functional acceptance testing and FVC thruster alignment checks. FVC thruster module vibration testing was deferred to the spacecraft level.

Subassembly-Level Hydraulic Testing

Following fabrication of the NEAR propulsion system hydraulic assembly (total system minus the LVA thruster and FVC thruster modules), the system was hydraulically tested to establish the proper pressures at the FVC module interface and the proper pressures and flow balance at the LVA thruster interface. During this test, the system was loaded with water to the flight-volume level and pressurized to flight pressure; then the typical LVA and FVC thruster burn sequences were executed. Final selection of the flow control orifices established an LVA operating mixture ratio of 0.725. The LVA thruster subassembly was acceptance tested before integration with the hydraulic subassembly.

System-Level Vibration Testing

After installation of the LVA thruster and flow-control orifice, the propulsion system was sine and random vibration tested (FVC thruster modules not attached). During vibration testing, the propellant tanks were loaded with water to flight-mass level and pressurized to flight pressure, with the helium tank loaded with nitrogen to flight mass and to 47.6 atm. Before and after vibration testing, the propulsion system underwent electrical acceptance testing and LVA thruster alignment checks. The system was load tested using a 5–100-Hz sine test. Spacecraft acoustics were simulated using a 100–2000-Hz random vibration test. The structure and propulsion-system test spectra are given in Tables 5 and 6.

Thermal Vacuum Testing

After draining, drying, and integrating the FVC thruster modules and manifolds, the propulsion system was shipped to Ball Aerospace for thermal vacuum testing. Most of the thermal vacuum tests were conducted with a chamber-wall temperature of −30°C to simulate the conditions the core propulsion module would experience during flight. The final test rapidly chilled the chamber wall to −100°C and used the

Table 5. NEAR structure and propulsion-system vibrational test spectra for a sinusoidal testing environment.

Axis	Frequency (Hz)	Acceleration
z	5 to 22	9.65 mm (double amplitude)
z	22 to 23	9.4 G (zero to peak)
z	23 to 100	1.4 G (zero to peak)
x,y	5 to 11	15.8 mm (double amplitude)
x,y	11 to 12	3.8 G (zero to peak)
x,y	12 to 100	1.0 G (zero to peak)

Table 6. NEAR structure and propulsion-system vibrational test spectra for a random testing environment.

Frequency (Hz)	Power spectral density level
100	0.001 g^2/Hz
100 to 300	+9.3 dB/octave
300 to 700	0.03 g^2/Hz
700 to 2000	−3.2 dB/octave
2000	0.01 g^2/Hz

thermal inertia of the spacecraft structure simulator (that surrounded the propulsion system) to slowly reach −30°C to simulate the conditions the FVC thruster modules would experience in flight. After thermal vacuum testing, the propulsion system was delivered to APL, underwent final system electrical acceptance tests and proof and leak tests, and was integrated into the spacecraft structure.

Spacecraft-Level Testing

Once integrated with the spacecraft structure, the propulsion system was loaded with water and subjected to spin balance, sine and random vibration, and acoustic and separation shock testing. After spacecraft mass properties were determined, a final LVA alignment was completed. After the water was removed from the propulsion system, the spacecraft was subjected to thermal vacuum balance and vacuum thermal-cycle tests. After delivery to Cape Canaveral, Florida, the propulsion system underwent final proof, leak, and functional testing, propellant loading, pressurization, and integration with the Delta launch vehicle.

MISSION OPERATIONS

The baseline mission profile (Table 1) shows only three or four individual LVA burns for the NEAR mission. These burns include two final oxidizer depletion burns (one per tank) to exhaust all the oxidizer from the system before arrival at Eros. After oxidizer depletion, the mission trajectory will be trimmed using the ΔV capability of the FVC thrusters. Eros operations will use the FVC thrusters to adjust the inspection orbit parameters and adjust spacecraft momentum, as required.

Operation of the NEAR propulsion system is divided into five different maneuvers: FVC firing after launch, FVC firing in blowdown mode, FVC firing in pressurized mode, LVA firing, and LVA oxidizer-depletion firing.

During most of the mission, the propulsion system is disabled with all latch valves closed and only tank, line, and thruster heaters and telemetry enabled.

For a typical FVC thruster maneuver, the system is prepared by first powering the required catbed heaters 2 h before the scheduled burn, bleeding in the fuel lines using the fuel bleed valve, opening the appropriate fuel tank outlet latch valve, and pressurizing the system (if required) by opening the high-pressure latch valve. FVC thrusters are then fired, as required.

For a typical LVA thruster maneuver, the system is prepared just as if the planned burn were a regulated FVC maneuver. The four 22-N monopropellant thrusters are then pulsed at a 12% duty cycle (120 ms on, 880 ms off) for 200 s to settle the oxidizer over the tank outlets. Once settled, the appropriate oxidizer tank outlet latch valve is opened, after which the oxidizer pressure inlet latch valve is opened. The LVA thruster is then fired. During an LVA oxidizer depletion burn, a drop in LVA thrust below 70% for longer than 2 s is detected by the spacecraft and the LVA thruster is shut down. The system is secured after any burn by closing all valves and powering down the catbed heaters.

Spacecraft center of mass must be maintained to within ±20 mm throughout the expulsion of all the loaded propellant. Rather than open all latch valves, the NEAR approach sequences individual tank latch valves for a given duration and overlap. Analysis shows that by using a 30-s open duration with a 2-s overlap, center-of-mass travel in a plane perpendicular to the LVA thrust vector can be maintained to ±2 mm, well within the control authority of the large FVC thrusters during LVA firings. Large FVC thrusters can compensate for thrust vector and/or center-of-mass offsets up to 35 mm.

Status and health of the propulsion system in flight are provided by telemetry of nine latch-valve positions, five pressures, fourteen temperatures, and two currents, as well as nine commandable heater and power enable relays.

FLIGHT DATA

In the first 12 months of operation, the propulsion system provided attitude control during the postseparation period, a momentum dump, and five trajectory-correction ΔV maneuvers. The reconstructed values of propellant consumption for the seven maneuvers are summarized in Table 7, along with the propellant inventory.

Pressure and temperature tracking from launch to March 1997 is shown in Figs. 5 and 6, respectively. Activation of the pressurization system was scheduled to occur just before the July 1997 deep space burn.

PROGRAMMATICS

The Aerojet Propulsion Company designed, developed, fabricated, and tested the propulsion system under a cost-plus-delivery incentive-fee contract with APL. Aerojet was also responsible for the preflight checkout and propellant loading operations.

Aerojet empowered a small, colocated integrated product team (six people) and used specialists for analysis and tests, as needed. By using ProEngineer solid-modeling design software, the designers generated their own level 2 documentation. Most of the system assembly and testing was performed by the design engineering team, including the design and construction of the ground support equipment used for testing.

APL employed a small companion team (two people) for contract monitoring and for performing spacecraft integration and testing, spacecraft interfaces, and mission operations. Frequent contact by phone, fax, and e-mail among team members at Aerojet and APL was encouraged and was used in areas such as structure design, interfaces, and test documentation.

At the start of the program, Aerojet was able to quickly establish fixed-price letter subcontracts for all the major flight components and materials. Components were all delivered on schedule, and the final 6 months of system integration and testing went essentially according to plan. In accordance with the contract, the system was delivered to APL in Boulder, Colorado, on 12 May 1995, only 16 months after the initial authority-to-proceed date. Shipment and checkout took 1 week, and the system was declared ready for spacecraft integration on 19 May 1995.

The small team approach, extensive use of computer drafting and documentation tools, minimal oversight, and limited documentation requirements all contributed to containing the cost of developing this complex system. Meeting the short 16-month delivery schedule was the major cost driver and required significant overtime for the small team. The ability of the small team to meet the schedule minimized long-term man-loading (“marching army”) type costs.

CONCLUSIONS

A dual-mode propulsion system was successfully designed, manufactured, tested, and delivered in just 16 months. The accomplishment shows that the integrated product team approach can be used successfully on complex systems. Flight performance to date has verified the soundness of the design.

The system incorporated a composite structure to minimize structure weight and flight-proven components to minimize cost, schedule, and reliability risk. The 12 thrusters provide $+x$ ΔV and redundant 3-axis

Table 7. Propellant inventory.

Activity	ΔV (m/s)	Fuel used	Cumulative fuel used	FT1 fuel left	FT2 fuel left	FT3 fuel left	OT1 fuel left	OT2 fuel left
Liftoff	0.000	0.000	0.000	71.63	71.63	71.63	54.52	54.52
Detumble	0.066	0.057	0.057	71.57	71.63	71.63	54.52	54.52
Momentum dump	0.115	0.041	0.098	71.53	71.63	71.63	54.52	54.52
TCM-1	9.398	3.395	3.493	70.52	70.59	70.29	54.52	54.52
TCM-2A	2.116	0.741	4.234	69.78	70.59	70.29	54.52	54.52
TCM-2B	0.151	0.055	4.289	69.72	70.59	70.29	54.52	54.52
TCM-3	0.056	0.020	4.309	69.72	70.57	70.29	54.52	54.52
TCM-4	0.106	0.038	4.347	69.72	70.53	70.29	54.52	54.52

Note: All values are in kilograms, except for ΔV. TCM = trajectory correction maneuver, FT = fuel tank, OT = oxidizer tank.

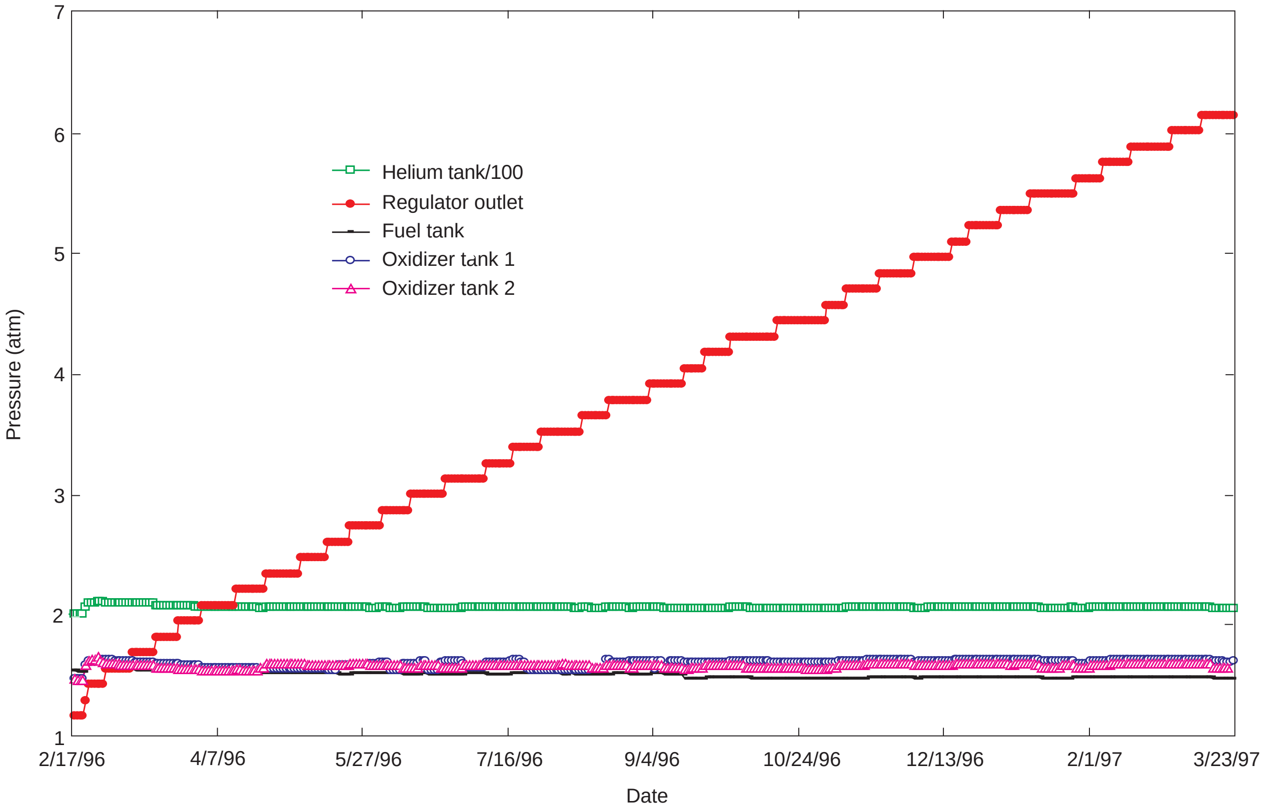


Figure 5. NEAR pressure tracking.

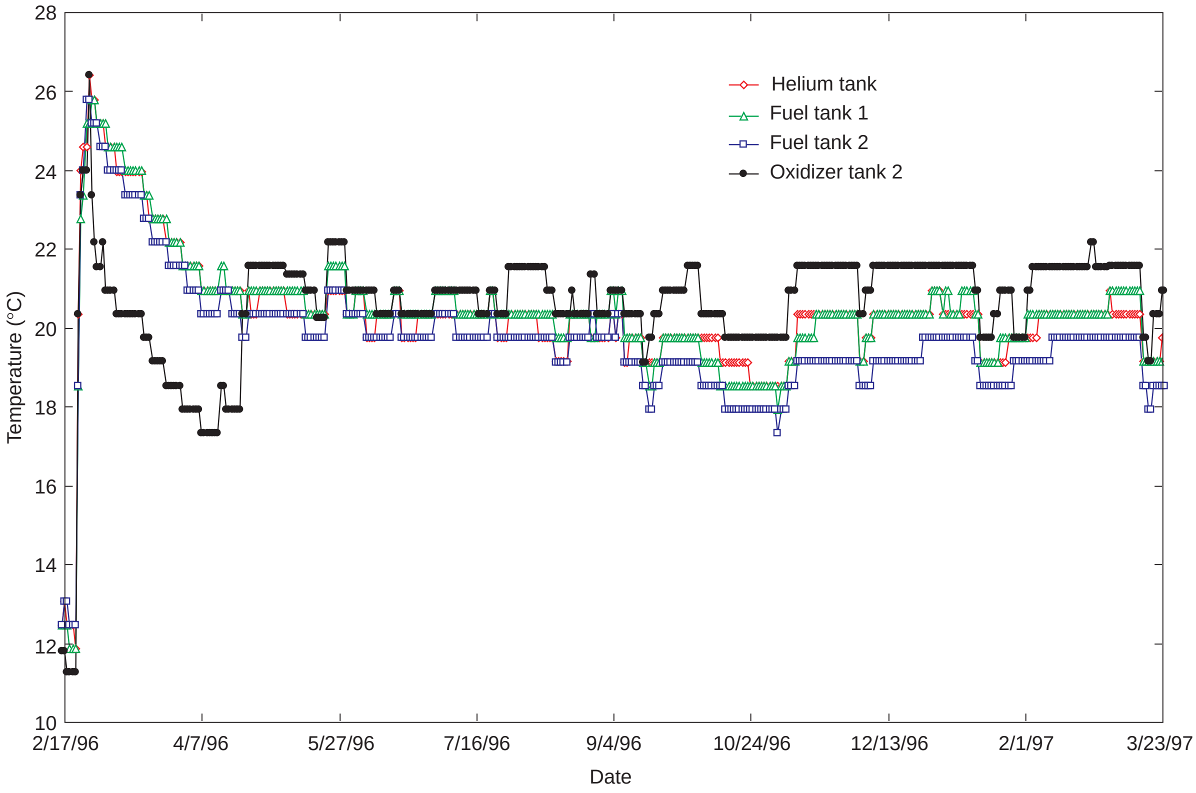


Figure 6. NEAR temperature tracking.

attitude control. For the NEAR mission, the system contains 318 kg of propellant but has tank-volume capacity for up to 425 kg. With a 118-kg dry weight, this equates to a maximum propulsion system mass fraction (including structure, harness, and thermal control but no electronics) of 0.78.

Future applications could benefit from the capability of the propulsion system's composite structure to augment or even replace the spacecraft structure, resulting in an even lighter, more capable spacecraft.

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