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INITIAL CASSINI PROPULSION SYSTEM IN-FLIGHT CHARACTERIZATION

ABSTRACT FOR PAPER SUBMITTAL/APPROVAL (October, 2001)

The Cassini Propulsion Module Subsystem (PMS) has performed excellently during four years of mission operations. Lockheed Martin Astronautics (LMA) provided the PMS to the Jet Propulsion Laboratory (JPL) under NASA contract. Cassini is an ambitious, international interplanetary mission to the planet Saturn consisting of a Titan atmospheric entry probe named Huygens provided by the European Space Agency and a Saturn orbiter contracted by JPL. A VVEJGA (Venus-Venus-Earth-Jupiter Gravity Assist) interplanetary trajectory was utilized to obtain sufficient orbital energy to reach Saturn. Cassini was launched on a Titan IV/Centaur on October 15, 1997, on a seven-year, two-billion mile journey to the ringed planet. Saturn arrival will be July 1, 2004.

The Cassini PMS is actually two complete propulsion systems in one integrated assembly. It contains a pressure-regulated liquid bipropellant system for large trajectory correction maneuvers (TCMs), utilizing earth-storable, hypergolic propellants. It also contains a monopropellant blowdown hydrazine system (with one-time recharge capability) for attitude control and minor trajectory corrections. The fuel for the bipropellant system is monomethylhydrazine (MMH) and the oxidizer is nitrogen tetroxide with 3% nitric oxide (MON-3). High-pressure helium gas is stored in a pressurant tank and is provided as needed via a pressure regulator to the two bipropellant tanks. The bipropellant system has an intricate pressurization system that includes high-pressure latch valves, quad redundant check valves, and a myriad of pyrotechnic valves for positive NTO vapor isolation, as well as for contingency operations.

The PMS retinue of rocket engines includes sixteen 0.9-N monopropellant hydrazine thrusters, eight primary thrusters and eight spares. The axial (Z-axis) thrusters are used for axial velocity increments in small TCMs, as well as for pitch and yaw control for the three-axis stabilization of the Cassini spacecraft. The roll (Y-axis) thrusters are used exclusively for roll axis control.

In addition to the assortment of hydrazine thrusters, there are two main bipropellant 445-N engines for large delta-V maneuvers, including Saturn Orbit Insertion (SOI). Bipropellant TCMs are performed by firing only one of the main engines. The second main engine is provided for contingency situations. Pitch and yaw control is achieved via engine gimballing, while roll rates are controlled during main engine burns by firing Y-axis thrusters. Ten 445-N main engine burns have been executed by Cassini to date. TCM-5, known as the Deep Space Maneuver (DSM), was a 90-minute plane change maneuver that was essentially a test of SOI, at least with respect to propulsion system operation. Only two monopropellant TCMs have been executed to date.

An assessment has been made of PMS telemetry (mostly pressures and temperatures) during four years of mission operations. Generally, the trends seen in PMS data are as expected and are well understood. For example, difference plots of multiple pressure transducer channels vs. time have demonstrated no discernible pressure transducer drift. This is in stark contrast to the linear pressure sensor drifts noted on other interplanetary missions (e.g., TOPEX, Voyager, and Galileo, cf. AIAA-97-2946, ``Final Galileo Propulsion System In-Flight Characterization▒).

PMS consumables have been tracked since launch, including propellant usage, thruster valve cycles, latch valve cycles, etc. Consumable usage has generally been close to predicted values. The life-limiting consumable for the propulsion system will probably be propellant, most likely hydrazine. In fact, hydrazine will probably be the mission-critical consumable. More than 90% of the launch load of hydrazine remains on-board, but the four-year Saturnian tour will require large expenditures of monopropellant. An extensive hydrazine usage prediction and budgeting exercise is now underway.

Maneuver performance has generally been excellent. Main engine maneuvers are terminated via accelerometer control. As such, the main engine maneuver accuracy has improved with better characterization of the attitude control system, especially calibration of the accelerometer. Monopropellant system maneuvers have also been sufficiently accurate, though the thruster duty cycles during these TCMs suggest a large, unexpected error in the location of the spacecraft center of mass.

Attitude control thruster performance has been investigated during limit cycle thruster firings. Actual impulse bits as delivered by the thrusters consistently exceed the thruster ground models for impulse bit vs. on-time. These data may help refine the impulse bit models, which will lead to better models of pulse-mode hydrazine consumption. In fact, the proposed modifications to the impulse bit models suggest hydrazine usage values that much more closely match hydrazine consumption values determined from hydrazine tank pressure and temperature models.

A helium budget exercise was undertaken as a ``health check'' for the Cassini PMS, both in the monopropellant and bipropellant portions of the propulsion system. Tank pressure and temperature data was combined with propellant mass estimates to determine the amount of helium in the propulsion system. Discrepancies in this helium budget indicate possible internal or external leaks, inaccurate modeling of propellant consumption, pressure transducer drift, etc. Cassini helium budgets have generally been nominal, at least with respect to external leakage.

During the mission to date, the most notable propulsion anomaly has been an apparent large leak in the hard-seat, primary pressure regulator. A real-time command was sent to close an upstream high-pressure latch valve during initial pressurization, since the tank pressure kept increasing linearly above the regulator lock-up point. The leakage characteristics of this regulator were far out of specification at initial pressurization, and the apparent leak rate increased by another factor of six for the DSM. Most likely, this large leak is associated with particulate contamination. A scratched regulator ball or seat is not as likely, since the apparent leak rate increased so dramatically during the mission. It has also been suggested that the regulator is exhibiting a soft lock-up due to the flow conditions specific to the Cassini design (large downstream volumes, flow through a high-pressure latch valve, etc.). Perhaps a shift in the regulator lock-up pressure is a possible explanation as well. Regardless, the behavior of the pressurization system has caused modifications to the operation plan of Cassini, particularly for pressurized bipropellant maneuvers, including SOI.

The initial in-flight characterization of the PMS is now complete. All critical functions that will be required for the remainder of the mission, including orbit insertion, have been demonstrated. In summary, the Cassini PMS has performed very well during four years of mission operations to date. The prospects for a successful orbital tour of Saturn remain excellent.