Dawn Spacecraft Reaction Control System Flight Experience

Masashi Mizukami[1] and Barry Nakazono[2]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

The NASA Dawn spacecraft mission is studying conditions and processes of the solar system's earliest epoch by investigating two protoplanets remaining intact since their formations, Ceres and Vesta. Launch was in 2007. Ion propulsion is used to fly to and enter orbit around Vesta, depart Vesta and fly to Ceres, and enter orbit around Ceres. A conventional blowdown hydrazine reaction control system (RCS) is used to provide external torques for attitude control. Reaction wheel assemblies were intended to provide attitude control in most cases. However, the spacecraft experienced one, then two apparent failures of reaction wheels. Also, similar thrusters experienced degradation in a long life application on another spacecraft. Those factors led to RCS being operated in ways completely different than anticipated prior to launch. Numerous mitigations and developments needed to be implemented. The Vesta mission was fully successful. Even with the compromises necessary due to those anomalies, the Ceres mission is also projected to be feasible.

I. Introduction

The Dawn mission is part of the NASA Discovery program of mid sized science spacecraft. It will study two of the largest bodies in the asteroid belt, Ceres and Vesta, with the goal of gaining insight into the early history of the solar system (Figure 1). Dawn is one of few science mission to use ion engines for primary propulsion.[1]

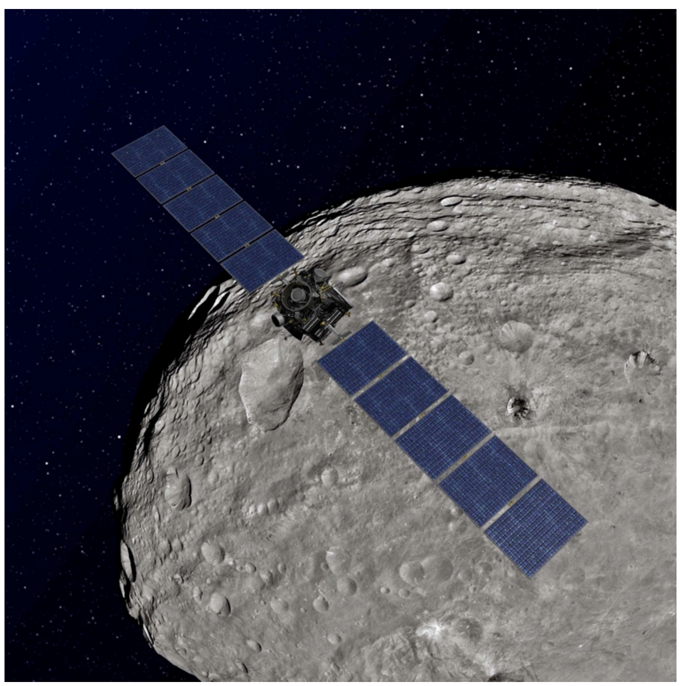

Figure 1. Dawn spacecraft image shown in orbit around Vesta *Image credit NASA/JPL-Caltech*

[1] Propulsion Engineer, Propulsion and Fluid Flight System Group
[2] Propulsion Engineer, Propulsion and Fluid Flight System Group

The ion propulsion system (IPS) provides capability for an unprecedented 11 km/sec of total propulsive in-space velocity.[2] IPS will perform heliocentric transfer from Earth to Vesta, orbit capture at Vesta, transfer to a low Vesta orbit, departure and escape from Vesta, heliocentric transfer from Vesta to Ceres, orbit capture at Ceres, and transfer to a low Ceres orbit. The transfer from orbit around one deep space body to another will be the first ever. A representative trajectory is shown in Figure 2.

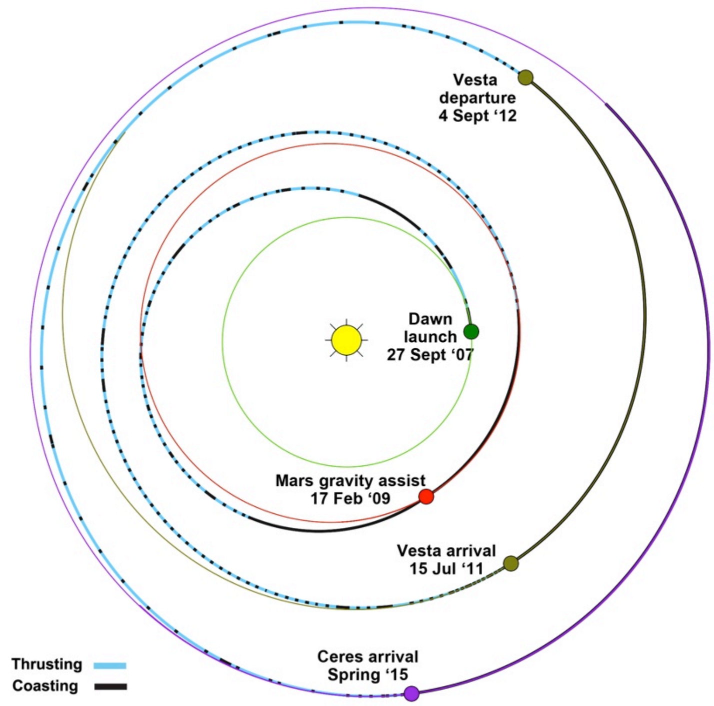

Figure 2 Dawn Trajectory *Image credit NASA/JPL-Caltech*

The reaction control system (RCS) is a conventional monopropellant, blow-down type. A schematic is shown in Figure 3. There is a single spherical, titanium alloy-wall propellant tank, with an elastomeric diaphragm positive-expulsion device. Nitrogen was utilized as the pressurant gas. The propellant distribution module incorporates a filter, redundant pressure transducers, and latch valves separating each of two thruster branches with six small Rocket Engine Assemblies (REAs). The two branches provide redundancy.

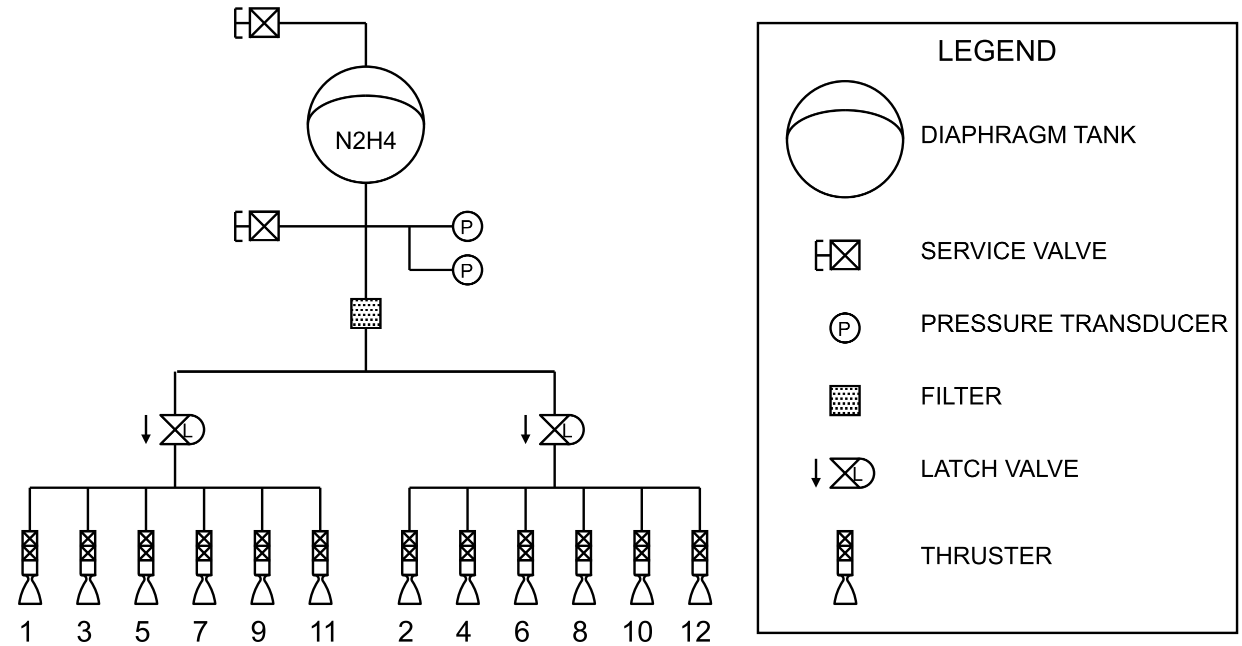

Figure 3 RCS schematic

The thrusters are located on the spacecraft as shown on Figure 4 in a "folded-out" view. Thrusters on the +X and -X spacecraft faces, when fired in opposing pairs, provide nominally pure coupled moments about the Z axis. Moments about other axes are not pure couples, imparting a net delta-V to the spacecraft.

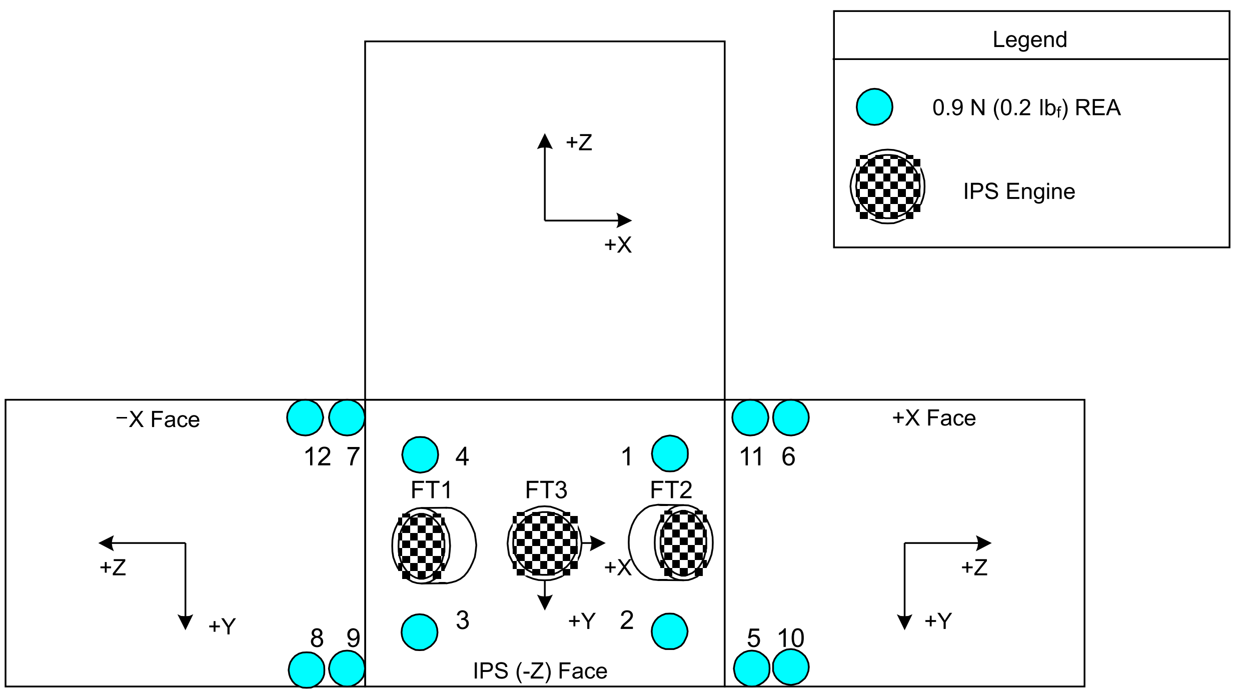

Figure 4 RCS thruster layout, "folded-out" spacecraft view

Attitude control was designed provided by reaction wheel assemblies (RWA), in conjunction with IPS thrust vector control (TVC) while thrusting, with RCS performing periodic desaturation firings (desats) to reject momentum. Dawn has four RWAs, three of which are required for full control. During cruise to Vesta, one RWA experienced a severe anomaly and could not be returned to operation. In order to preserve the three remaining RWAs for science operations, attitude control was switched to all RCS, supplemented by TVC when thrusting. For Vesta operations, attitude control was switched back to RWA, to provide tighter pointing accuracy for science observations, and to conserve hydrazine over numerous slews. Near the end of the Vesta phase, a second RWA apparently failed, which was fortuitous timing. Attitude control was once again switched back to RCS. Meanwhile, 'hybrid' mode attitude control was being developed using a combination of RCS and two remaining wheels, with the goal of providing better pointing accuracy and lower hydrazine consumption than all RCS.[3] As a result of those RWA anomalies, the Ceres mission had to be re-planned. Because the RWA failures appeared to be systematic, a strategic decision was made that the Ceres plan should be executable even if a third RWA failure occurs, in all-RCS mode. If two RWAs remain healthy and at least a portion of the plan can be executed in hybrid mode, then some bonus science could be obtained late in the mission.[4]

This paper presents the flight experience with Dawn RCS to date. Mainly as a result of RWA anomalies, RCS is being operated in ways completely different than anticipated prior to launch. Flight performance is described. Developments and operational changes are explained. Lessons learned are discussed.

II. Subsystem Operation

RCS operation was originally anticipated to be routine and straightforward. However, a number of unanticipated events made things more interesting.

A. Trajectory Control Maneuver

On many spacecraft RCS can be used for small delta-V maneuvers, and Dawn was designed with this contingency capability. During initial checkout, a small validation / calibration burn was performed. The maneuver was successful, magnitude and pointing accuracy were about as expected, and the thruster performance was calibrated. However, no RCS maneuvers have been performed since then, and none are planned. Even small trajectory control maneuvers during asteroid orbit operations are performed using IPS.

B. Thermal Control

Thermal control is an unglamorous but critical aspect of propulsion operations. Component temperatures must be maintained with the respective allowable flight temperatures, which are typically based on qualification test temperature ranges, with margin. Temperatures of wetted portions must be kept above freezing point of hydrazine (2 °C) at all times, with margin. Wetted line temperatures must be below a reasonable limit to keep hydrazine decomposition rates acceptably low, and also consider convection of hot propellant into temperature-limited components. In the tank, it is desirable to keep the pressurant portion warmer than the propellant, in order to reduce condensation of propellant vapors on the pressurant side.

Control of propellant line temperatures is challenging, because of the sprawling geometry, and low thermal mass. The lines were divided into a number of zones of control. Each zone typically had several surface temperature sensors, of which one or more was used for 'primary' control, some others were used for 'redundant' control, and a different set may be monitored by fault protection. Also, some zones also have mechanical thermostats for additional protection against freezing. Thermal vacuum test data was useful for guidance, but was not a complete simulation, because the propulsion system was dry, with no propellant flow, and heat sources such as solar flux and thrusters were not simulated. As a result, line temperature control setpoints and fault protection monitor levels needed to be adjusted numerous times after launch.

Thruster valve heaters are software controlled based on measured temperature. Control setpoints were slightly raised to equal propellant temperatures used during thruster life qualification test, because lower temperature hydrazine may reduce catalyst bed life.

It was found that -Z thrusters are closely thermally linked to the metal brackets they are mounted on, which in turn are adhered to the spacecraft composite primary structure. When the -Z face was away from sun, significant heat loss could potentially cause thruster valve temperatures to decrease below safe levels. Therefore as a protective measure, bracket heater control setpoints were increased to decrease heat loss from the valves. Conversely, when the -Z face was pointed towards the sun, heating would increase temperatures to unsafe levels. Therefore, thermal engineers performed analyses, and established a new flight rule to disallow pointing of the -Z axis within a certain angle of the sun, depending on solar distance. Interestingly, because of the particular hardware configuration and shadowing, the even branch has less constraints than the odd branch.

Catbed heaters draw a substantial amount of power. The original plan was to keep the primary branch catbed heaters fully on, but control the backup branch catbed heaters to a near ambient temperature range to reduce power consumption. In the event of a fault protection response that causes branch swap, a cold start would occur, a certain number of which is allowable, but not a potentially frozen start that could damage hardware. Also, upon further analysis, it was found that resulting numerous cycling of the catbed heater was only qualified by similarity[5], with a possibility of partial failure during the mission. Early in the mission there is plenty of excess power available, so to mitigate those risks, both branch catbed heaters are run fully on. Later in the mission, farther from the sun, the spacecraft will be more power limited, so the backup branch may be actively controlled lower temperature, to allow higher ion propulsion thrust level and improved mission performance.

In another effort to save power, spacecraft panel heater setpoints were decreased. However, propellant lines are routed under the panel and could be thermally affected. For example, decreasing the panel temperature actually increased the magnitude of a temperature spike that occurs upon initiation of propellant flow. This is probably because lower surrounding temperature caused line heaters to operate at a higher duty cycle, increasing magnitudes of hot spots. Attitude control system (ACS) behavior also affected the quantity of propellant flow, which in turn affected temperatures spike magnitude. In a case where the temperature spike became high enough to be of concern, the panel heater setpoint change was backed out, and the temperature spike magnitude decreased..

C. Branch Swaps

The odd and even thruster branches provide redundancy. In case of branch swap due to autonomous fault protection action or due to operator commanding, operation is intended to be seamless.

After launch vehicle separation, the spacecraft was spun down using RCS thrusters. The Delta II launch vehicle has a high spin rate during third stage solid rocket motor burn. However, Xenon in the IPS propellant tank spun down slower than expected [6], causing fault protection to suspect an RCS problem, and swap from the odd to even branch. Subsequently, the spindown was completed successfully. Because the branches are functionally identical, it was decided to continue flying on the even branch, and not perform an unnecessary swap back to the odd branch.

Later in the mission, due to fault protection action, an autonomous swap from even to odd branch occurred. After resolution of the underlying issue, a swap from odd to even branch was commanded from ground. This was because the even branch has less restriction on sun angles, and the plan called for operating on the even branch. RCS performance was nominal through those activities.

D. Safe Modes

Dawn safing includes pointing the high gain antenna to the sun using sun sensors, establishing a slow spin rate about sunline, and using low gain antennas for communication. RCS is used to slew the spacecraft and impart spin rate, but nominally returns to RWA control once safe mode is established. However, when more than one RWA is unavailable, safe mode remains in RCS control. Testbed simulations of indicated that hydrazine consumption while in safe mode may be extremely high. This would require a large contingency allocation of hydrazine to cover the anticipated number of safings, and also apply additional time pressure to recover from safe mode quickly. Investigation by ACS personnel revealed that an unrealistic sun sensor misalignment programmed in the testbed may be causing extraneous attitude perturbations to be commanded. Subsequent testbed runs with more realistic sun sensor alignment had much lower hydrazine consumption rates in safe mode. This allowed the contingency hydrazine allocation to be reduced, making more of it available for the planned mission. As of writing, no actual all-RCS safings have occurred.

E. Thruster Degradation Risk Mitigation

Typical possible degradation modes for small hydrazine thrusters are catalyst breakdown, plugging of small orifices, or catalyst contamination. If continued to operate in a highly degraded state, it may lead to an uncontained failure. In late 2008, another JPL operated spacecraft, Cassini-Huygens, experienced degradation of its RCS thrusters earlier than anticipated. The degradation could be observed in chamber pressure roughness, reduce performance for delta-V maneuvers, and reduce thrust during RWA biases. RCS was swapped to the backup branch soon thereafter. In the ensuing investigation, potential causes identified were silicon leaching from the tank diaphragm, operation at an untested combination of duty cycles, thruster lot-to-lot differences, and feed line interaction. Operational mitigations proposed include momentum biasing using a subset of thrusters, monitoring thruster health and performance more closely, and minimizing usage of untested combinations of duty cycles.

However, no single root cause could be identified. To obtain a clearer identification of the causes, and potential future risk, a test program was recommended.[7]

Dawn thrusters are not identical to Cassini's, but based on the findings, mitigations were applied where possible. Thruster starts are tracked as a consumable. RCS consumable allocations were revised based on a different qualification test. Additional processes are planned to to monitor thruster health and performance. Thruster valve temperature control setpoints were adjusted to more closely match qualification testing. During thrusting, RCS-TVC attitude control will be used to reduce starts from periodic desats.

F. Thrust Monitoring

Methods for monitoring thrust in-flight are being considered. As mentioned, thrust decrease is an indicator of hydrazine monopropellant thruster degradation. When performing momentum biases while in RWA control, momentum change could be used to calculate impulse imparted by thruster firing, which can be compared with expected impulse from thruster models. When slewing or maintaining attitude in RCS control, angular rate changes could be used to calculate impulse imparted by thruster firing, which can be compared with expected impulse from thruster models. As on most spacecraft, Dawn thrusters do not incorporate pressure transducers, so it is not possible to monitor actual chamber pressures and roughness. RCS delta-V maneuvers would be an excellent opportunity to easily measure in-flight thrust, but Dawn generally does not perform RCS maneuvers.

III. Attitude Control

RCS is closely tied with ACS, and could even be considered an actuator of ACS, along with RWA and IPS TVC.

A. RWA with RCS Desaturations

In the original mission plan, attitude control would be provided by RWAs, in conjunction with IPS TVC while thrusting. Momentum would be periodically rejected by desaturation or 'desats,' by firing RCS thrusters in pulse trains to bring spacecraft momentum to the desired state. Desats usually occur by sequenced commands, but may also occur autonomously if certain limits are exceeded.

B. All-RCS

When all-RCS control was first used over an extended time, there was frequent pulsing of all thrusters, and thrashing back and forth between the attitude deadband limits. Dawn ACS was originally never intended to be operated in all-RCS control over an extended period of time. To remedy the situation, deadband limits and gains were relaxed, particularly on the non-critical pointing axis. This could be accomplished with a parameter load, without an actual flight software update. After this change, hydrazine consumption rate in typical pointing modes were much lower, a few grams per day.

Due to basic physics, RCS slews require a substantial amount of propellant, to accelerate the spacecraft to a target angular rate, and a comparable amount to decelerate back to zero, with some additional amount to maintain control within some bounds. To conserve hydrazine, slew angular rates were reduced to a half, then to a quarter of the original. Hydrazine savings were nearly proportional to the rate reduction, as anticipated.

When transitioning to a control with tighter deadband limits, there is a transient where thrusters fire to bring control within the tighter band. Unfortunately, the control algorithm seems to overcorrect, and there is a significant amount of firing and hitting limits, before settling in the new control band, and the propellant consumed is several times what would be anticipated from a smoother transition. Additional parameter tuning is expected to mitigate some of the excess consumption.

Because of the unique pointing requirements and gravity gradients in Ceres orbit, extensive software and testbed simulations have been performed. To reduce hydrazine consumption, control bands were widened and the number of slews were reduced as much as feasible. Hydrazine consumption increases dramatically at lower orbits. The current plan is to fly most of the Ceres mission in RCS mode to preserve the indeterminate remaining RWA life, and fly the lowest orbit in hybrid control, described below, to reduce hydrazine cost. In case of a third RWA anomaly, the spacecraft will revert to RCS control.

C. Ion Propulsion Thrust Vectoring - RCS

When thrusting on IPS, an elegant way to maintain attitude control is to use RCS to counter the 'swirl torque' about the IPS thrust axis, and use IPS TVC gimbaling to control the other two axes.[8] RCS control exhibited the desirable one-sided dead banding, with no waste due to banging between both deadband limits. However, the pulse rate was fairly frequent. Unfortunately, two of three IPS thrusters would use the same RCS thruster to counteract swirl torque, and it was projected the pulse count limit of that RCS thruster would be exceeded. This had the unexpected consequence of constraining IPS thruster selection. Therefore, a parameter load was made to quadruple the minimum pulse width. Deadbanding was still one-sided, and the pulse count was significantly reduced. It is now projected the mission can be accomplished within thruster pulse count allocation, while maintaining flexibility to choose among IPS thrusters.

D. RWA-RCS hybrid mode

'Hybrid' mode attitude control is being developed using a combination of RCS and two remaining wheels. In principle, the two RWAs are used to control attitude about their spin axes, and RCS controls the remaining axis. Thrusters are also fired to desaturate the wheels when necessary. This should consume hydrazine at a lower rate than all-RCS control, because wheels can absorb and release momentum about two axes. Also, pointing accuracy can be tighter about the two wheel axes than in all-RCS control. Hybrid mode was certainly not anticipated pre-launch, and was developed following the first wheel anomaly. Many software simulation and testbed runs have been performed. Two brief in-flight demonstrations were successfully performed on the spacecraft. The current plan at Ceres is to fly in RCS mode to conserve the indeterminate remaining RWA life, and switch to hybrid mode only in the lowest orbit to reduce hydrazine cost.

IV. Consumables

Management of mission consumables is an important part of any spacecraft subsystem operations. This involves tracking the actual consumption, as well as projecting future consumption through the mission to completion. In addition to propellant quantity, measures of thruster life are managed.

A. Hydrazine

Propellant quantity is the ultimate consumable, in that when it is expended the subsystem ceases to function, and is the one most immediately associated with propulsion.[9] Propellant quantity was calculated using two different methods (Figure 5). In the "tank" model, propellant quantity was calculated based on tank pressure and temperatures. After some initial hydrazine usage, this was considered the most accurate indication of propellant quantity. However, there was too much noise to measure propellant consumption rates or events. In the "thruster" model, propellant usage was calculated based on telemetered thruster on-times and feed pressure. This was considered the most accurate measure of propellant consumption rates or events. However, inaccuracies in the flowrate model accumulate over time, and the estimate of propellant remaining may be inaccurate. Over time, it was found that the tank and thruster models were diverging considerably. This meant that propellant usage projections, using consumption rates based on the thruster model, could be highly inaccurate. An updated thruster model equation was received from the vendor. Using the new equation considerably reduced the discrepancy.

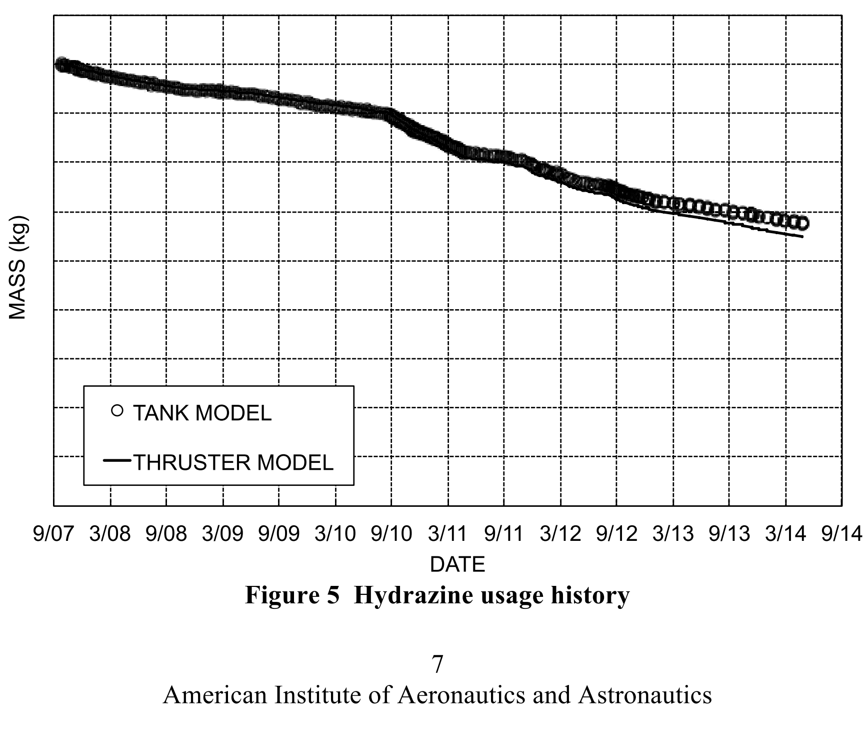

Figure 5 Hydrazine usage history

Future consumption through the mission was projected in support of mission planning. These were based on thruster model consumption rates to date. This is different from pre-launch propellant budgeting, where spec minimum performance values are used, because actual in flight performance with the particular hardware are not yet known. Also, with science spacecraft, the plan usually changes after launch, and the budget needs to be revised with new projections. In initial projections after the RWA anomalies, hydrazine required to fly the mission far exceeded the remaining usable quantity. Therefore, the project made it a priority to reduce propellant consumption. To this end, slew rates were reduced, the number of slews were greatly reduced and restricted, and hybrid mode development was initiated. Safe mode in RCS control was projected to consume vast quantities of hydrazine, but updated testbed runs indicated that consumption should be more reasonable. Now it is projected that even if there is a third RWA failure at Ceres, the mission can be completed while maintaining necessary margins and contingencies (Figure 6).

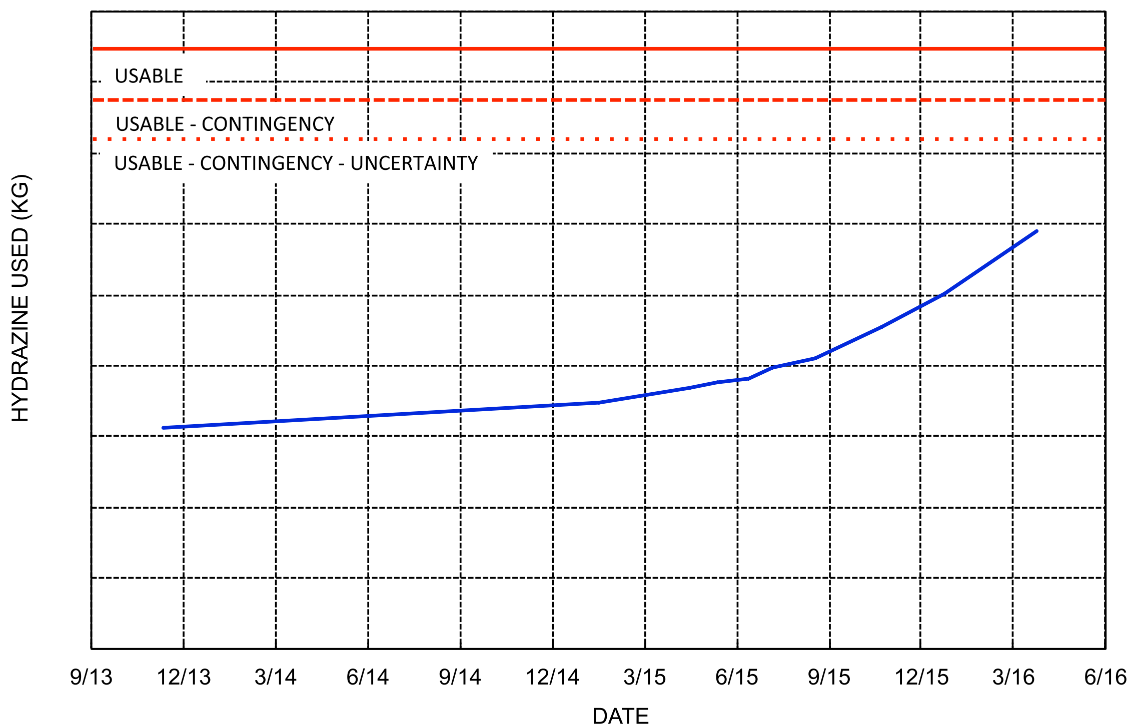

Figure 6 Hydrazine usage projection

In addition to planned usage, a certain amount is allocated as contingency for unplanned usage. This may include safe modes, and special activities that may be planned and executed along the way. The quantity allocated to contingency may be reduced or 'retired,' as the mission progresses if those amounts are not used.

Because the consumption rates used to project usage through the mission are inexact, it is appropriate to allocate a certain amount to uncertainty in projections. The quantity allocated to this uncertainty may also be retired as the mission progresses, as the actual quantity at future times are calculated from the tank model.

Unusable quantity includes the amount trapped in lines, components and between the diaphragm and tank wall, and but also the uncertainty in propellant gauging. This is because if the quantity cannot be measured, it cannot be depended upon to be available. To determine this value, an uncertainty analysis was performed of the tank model calculated propellant quantity, considering uncertainty of all the input parameters.

B. Pulses

For RCS thrusters are operated in pulse mode, pulse count is the next most commonly tracked consumable (Figure 7). But the reality is there are different kinds of pulses, and the effect on thruster life may vary depending on pulse duty cycle, pulse width, initial catbed temperature, propellant temperature, unit variability, etc. Therefore, the number of pulses in the qualification ground test is typically reduced by an empirical qualification factor to arrive at the flight allocation, to help account for those differences. As with hydrazine, initial projections after RWA failures indicated pulses will far exceeded the allocation during the mission. The issue was addressed in many ways: a different qual ground test with more pulses and sufficient starts was used to increase the allocation; minimum pulse width was increased to reduce pulse rate in RCS-TVC; efforts to reduce hydrazine consumption also generally reduced pulses; and operational adjustments will be made to better distribute thruster usage in hybrid mode. Now it is projected the mission can be flown within the pulse allocation.

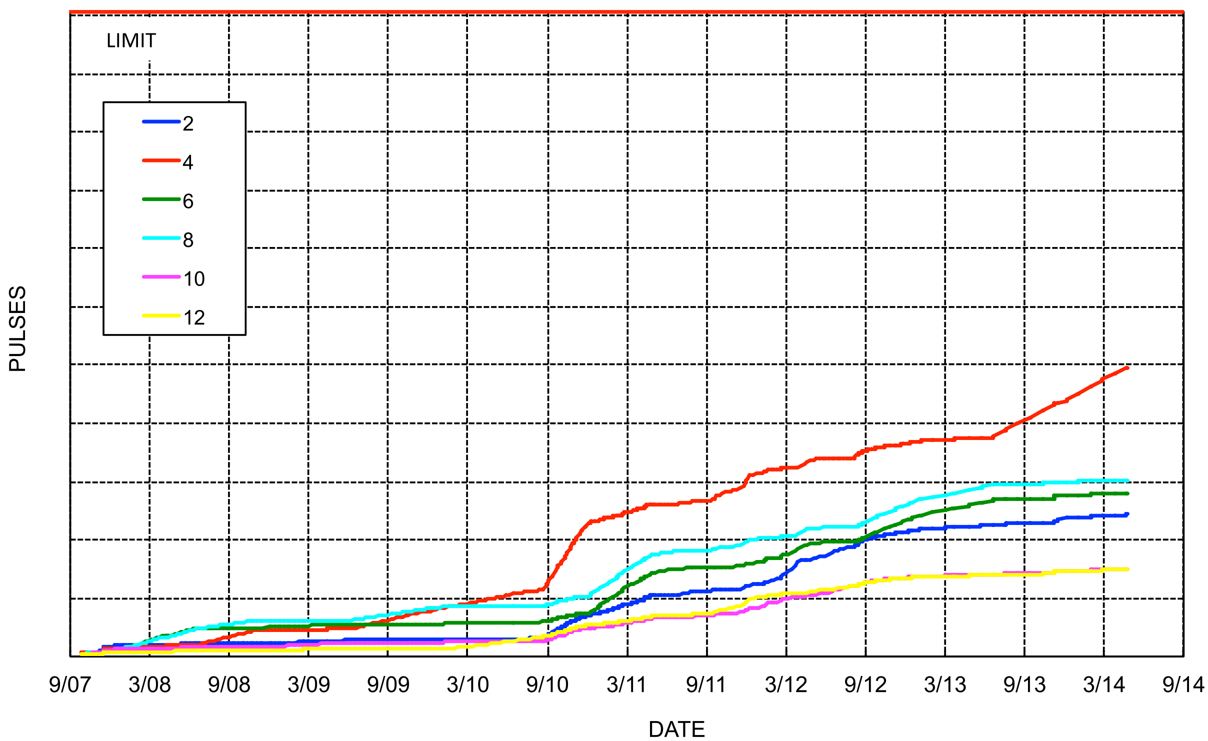

Figure 7 Pulse count projection

C. Starts

Recent experience indicated that thruster starts may be a life limiting factor, particularly those that involve large increases in catbed temperature. As with pulses, thruster start allocation was determined from ground qualification tests, de-rated by a certain qualificaiton factor. Limit cycle pulses are too short and isolated to be considered starts. Pulse trains for RWA desats or slews are considered a single start. In some other cases, deciding what constitutes a start was more subjective. In Ceres operations, based on testbed runs, atypical pulsing patterns are expected, and it will be more of a judgment call as to how to count starts.

V. Concluding Remarks

Dawn RCS is being operated in completely different ways than were anticipated prior to launch, mainly as a result of RWA anomalies. It has been successfully flown while cruising under ion propulsion and through the Vesta science encounter, part of it in all-propulsive attitude control. Related thruster anomalies during this time initiated a complete overhaul of the thruster life management approach. It is projected that the Ceres mission can be flown, even if a third RWA anomaly occurs, using all propulsive attitude control.

Acknowledgments

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