Odyssey Propellant Estimation Phenomenon: Mission in Progress - Mission Success

Boris Yendler[a]*, -Steven H. Collicott [b]

[a] YSPM, LLC 19190 Dagmar Dr. Saratoga, CA 95070
[b]Capstan Aerospace, LLC
*Corresponding Author

Abstract

The Odyssey spacecraft, launched in 2001, initially aimed to map the distribution of minerals and detect water ice on Mars. As the mission progressed, its primary role shifted to acting as a relay station for communication between the Mars landed assets and NASA's Jet Propulsion Laboratory (JPL), ensuring a reliable mission success.

In the later stages of the mission, a monopropellant propulsion system was utilized for station-keeping maneuvers, ensuring the spacecraft's correct orbit and orientation. The propulsion system featured two interconnected fuel tanks, which played a critical role in maintaining the spacecraft's stability during these operations.

For propellant usage estimation in addition to traditional propellant estimation methods, such as bookkeeping, thermal propellant gauging was exercised three times during the mission, in 2013, 2021, and 2022. The first two thermal propellant gauging measurements closely matched the bookkeeping estimates, providing confidence in the accuracy of the methods. However, the 2022 thermal gauging results diverged significantly from the bookkeeping estimates, raising concerns.

This discrepancy led to the formation of the Anomaly Resolution Team, which conducted a fishbone analysis to investigate the issue. The team explored various possibilities, including the impact of surface tension differences on fuel distribution within the spacecraft's tanks.

The investigation revealed that the fuel was moving back and forth between tanks through a fuel pipe, even though this movement was not expected. This unexpected fuel movement was significant enough to affect the accuracy of the thermal propellant gauging results.

By accounting for this fuel movement between tanks, the differences between the book-keeping and thermal propellant gauging results have been reconciled, bringing them into alignment and providing a better understanding of the spacecraft's remaining fuel.

Keywords: Propellant Gauging, Surface Evolver, Thermal Control

Acronyms/Abbreviations

Propellant Management Device (PMD)
Thermal Gauging Method (TGM)

1. Introduction

The **2001 Mars Odyssey** spacecraft has been the subject of numerous research papers and articles since its launch [1-3]. The **2001 Mars Odyssey** spacecraft utilized a **bipropellant propulsion system** designed for deep space maneuvers and orbital insertion around Mars. Key aspects of its propulsion system include.

- **Main Engine:** The spacecraft's main engine produced a thrust of approximately **695 Newtons (156 pounds)**. This engine was primarily used for the Mars Orbit Insertion (MOI) maneuver, a critical 20-minute burn that captured Odyssey into Martian orbit. This was the only use of the bipropellant propulsion system during the mission.
- **Attitude Control Thrusters:** For orientation and trajectory corrections, Odyssey was equipped with sets of small thrusters that performed attitude control and trajectory correction maneuvers, ensuring the spacecraft maintained proper orientation and navigational accuracy during its journey and operations around Mars.

In the later stages of the mission, a monopropellant propulsion system was utilized for station-keeping maneuvers, ensuring the spacecraft's proper orbit and orientation. The propulsion system featured two interconnected fuel tanks, critical for maintaining the spacecraft's stability.

2. Current Status

Propellant usage estimation was conducted using traditional bookkeeping method and the Thermal Gauging Method (TGM). The TGM was applied three times during the mission, in 2013, 2021, and 2022. The first two thermal propellant gauging measurements closely matched the bookkeeping estimates, providing confidence in the accuracy of the methods. However, the 2022 thermal gauging results diverged significantly from the bookkeeping estimates, raising concerns.

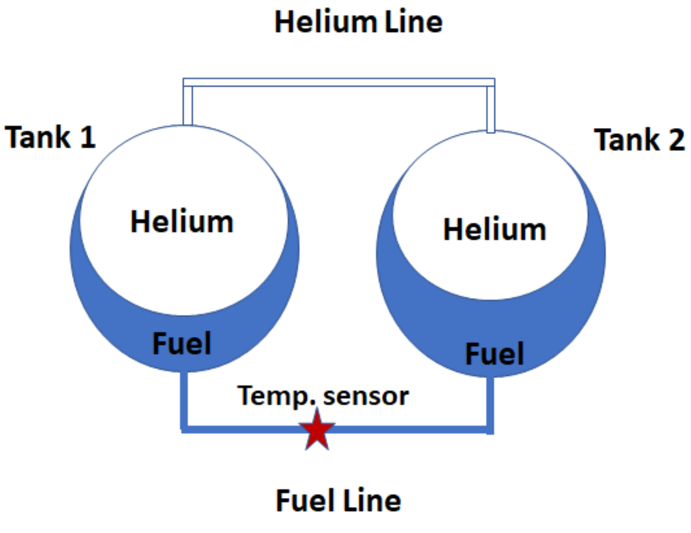

Fig. 1 Tank Plumbing

This anomaly prompted the formation of the Anomaly Resolution Team, which conducted a fishbone analysis. The team explored various possibilities, including the impact of surface tension differences on fuel distribution within the spacecraft's tanks [Ref.4]. It was shown that two identical connected tanks may have asymmetric fuel distribution as a stable state. This is the case for the Odyssey propulsion system. Due to tank affinity, equal fuel distribution between tanks is unlikely [Ref.4].

The propulsion system's tanks are connected by two lines: fuel and helium (see Fig.1). In addition to temperature sensors on the tanks, the fuel line includes a sensor and is maintained at elevated temperatures by a thermostat-controlled heater to prevent freezing.

3. Thermal Propellant Gauging

As was pointed in the Introduction section, the fuel load of the Odyssey s/c was determined by two methods, the book-keeping method, and the Thermal Gauging Method. While bookkeeping is accurate early in the mission, its precision decreases over time. In contrast, the Thermal Gauging Method (TGM) becomes more effective later in the mission.

The TGM is based on measuring heat capacity of a propellant tank by observing temperature rise when a known heat load is applied to a tank. A detailed description of the method can be found elsewhere [5]. Use of the TGM requires building high accuracy thermal models which include:

- Detailed knowledge of liquid distribution inside the tank
- Exact location of temperature sensors and heaters
- Full account of heat distribution, that is, (a) applied heat, (b) how much heat is rejected to the environment; (c) heat retained within the tank.

Detailed knowledge of liquid position is required to determine the condition of the tank wall at temperature sensor location. Obviously, readings are affected by the condition of the wall, whether it is wet or dry. Temperature distribution and heat retention depend strongly on liquid distribution. The tank often exhibits significant gradients, requiring accurate modeling of temperature sensor positions.

Exact position of temperature sensors and heaters are needed to simulate correct temperature distribution. Typically, tanks exhibit significant temperature gradients which require exact knowledge of temperature in a sensor location.

The cooling portion of the TMG is also important for an accurate estimation of the propellant load of a tank. Cooling is mostly governed by thermal connection between the tank and its environment. This allows precise determination and calibration of such a connection. Accurate modeling of heat loss during cooling enables improved calibration of this connection and leads to better fuel mass estimation.

A correct interpretation of TMG test results and, correspondingly, an accurate fuel load prediction requires accurate knowledge of the temperature distribution in the tank both during heating and cooling.

4. Modeling of Propellant Positioning in Tank

The *Surface Evolver* code [6, 7] was used to determine the static equilibrium positioning of the liquid propellant in the tank and PMD in weightlessness. Solving for liquid position in weightlessness is purely a geometry problem involving tank and PMD geometry plus the contact angle of the liquid on the solid. Liquid properties such as surface tension and density determine how much time is required to reach an equilibrium state, but they do not affect the shape of the equilibrium shape when in weightlessness. This modeling method produces 3D propellant distributions in the PMD and tank that are then used as input of mass distribution to the thermal modeling. *Surface Evolver* appears to remain uniquely powerful in this type of modeling, for CFD codes do not fare well with zero velocity fields and strong curvature of the free surface. That a 2D mesh on the free surface is used in a 3D problem instead of 3D grids in CFD provides an additional and very strong advantage to using *Surface Evolver* – the compute power of a common Windows notebook computer sufficed for all cases in this work.

Surface Evolver operates from a user-defined initial geometry, usually very coarsely meshed and generally the wrong volume, defined by triangular facets representing the liquid-vapor interface. Energies relevant to the problem at hand are defined by the user. In this case, the free surface energy of the liquid-vapor interface and the wetted surface energy of the liquid on the tank wall and PMD surfaces. The code then iterates through a scalar minimization routine, not equations of motion, to determine minimum energy solutions at the specified volume. Output from the result to be used in thermal modeling can range from fully complete, 3D coordinates of each corner of every one of many thousands of facets, to lower resolution summaries of propellant masses in various regions of the tank and PMD. Thus, *Surface Evolver* and CFD are complementary tools for the spacecraft fluids engineer, one is not better than another.

At the low liquid fill fractions of interest at this point in the mission, it is safe to assume a symmetric distribution of liquid in the tank [4]. Thus, one eighth of the tank with four PMD vanes is modeled. Vanes are modeled without thickness. The rigid tubes in the PMD are assumed to have wicked full of liquid, albeit a nearly negligible volume of liquid. Contact angle of the propellant on the tank wall and PMD surfaces is assumed small enough to model as zero. A volume of liquid is chosen, programmed into *Surface Evolver*, and careful interactive operation of the code, taking note of meshing problems which may arise, leads to a valid solution for positioning of the specified liquid volume. For zero contact angle, *Surface Evolver* is used to solve for gas location,

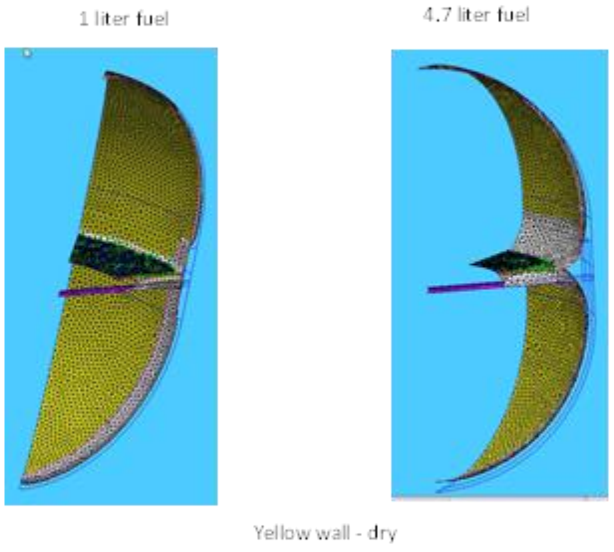

Fig. 2. Surface Evolver results

but this unambiguously then defines the liquid position as every point in the tank that is not occupied by gas or PMD. Small increments in volume about an existing solution are generally simple to calculate next, depending on the details of the geometry.

Modeling results show that the junction of the large annular baffle plate with the tank wall holds substantial liquid away from the tank drain at 10% and greater fill fractions. Yet this mass of liquid does not appear to be trapped, but appears to drain effectively, as seen in modeling down to the 0.5% fill fraction range.

Results of simulation liquid position in the tank are shown in Fig. 2. The yellow color indicates a dry wall. The white color shows the interface between liquid (fuel) and gas (Helium). Significant amount of the fuel is located around buffer and along PMD elements like vanes. With fuel load decreasing, the fuel is moving along the PMD to the bottom of the tank.

5. Modelling fuel flow

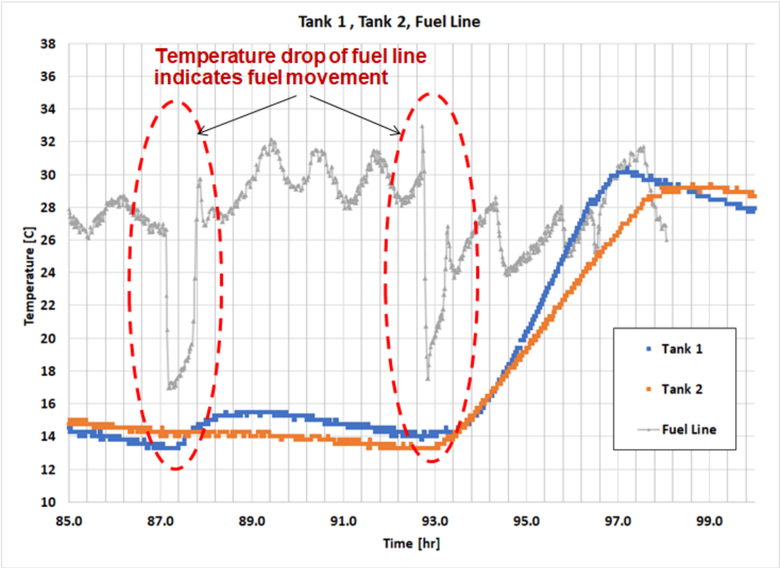

Fig. 3. Tank and Fuel line temperatures – flight data

Traditionally, the thermal method is used when propellant does not move in and out of the tank. Essentially, it behaves as a solid. The Surface Evolver model (discussed in the previous chapter) determines a propellant position which is used to determine temperature distribution in the tank. Assuming the constant heat capacity of the propellant in the tank and no flow, comparison of simulation with flight data allows finding the propellant mass.

If liquid moves in/out of the tank during heating/cooling, a mass and correspondingly heat capacity of the propellant in the tank changes during the test. Significant movement invalidates the static TGM model.

Flight data (Fig. 3) shows a significant temperature drop (up to 14 ^{0}C) in the fuel line. As was discussed earlier, fuel in tanks is kept at the temperatures well below fuel line temperature. A sudden drop of the fuel line temperature indicates fuel flow from one tank into another one (see Fig.3). The flow reverses direction afterwards.

Such fuel movement between tanks during the TGM operations necessitates a modification of the TGM approach in order to include fuel movement between tanks. A dynamic thermal model was developed using Dynamic Sinda to simultaneously simulate fuel flow and thermal response.

The fuel line has a separate heater controlled by a thermostat. This additional heat which is generated by the line heater should be included in energy input calculations pertained to the TGM. Unfortunately, the telemetry does not have ON/OFF heater status so the line heater contribution into a tank thermal balance can be only estimated. This creates an uncertainty of estimations by the TGM. Flight data was used to estimate the line heater contribution. The assessment indicated that the additional heating can be up 25% of total heat load. Previous estimations did not take into account fuel movement through fuel pipe which led to significant underestimation of propellant mass by TGM.

6. Discussion

If propellant mass does not change during heating, the shape of the heating curve should be either linear or convex due to energy loss to an environment. The concave shape of the heating curve suggests mass reduction during heating. The heating curves of tanks (flight data) is similar to one shown in Fig. 4 as a dash line. As Fig.4 shows if fuel movement is neglected and the slope of the heating curve determined as a difference between initial and final temperatures, the slope becomes steeper which indicates less fuel in the tank. This explains the reason why previous TGM estimations indicated less fuel load. Taking into account fuel movement between tanks corrects the results of fuel estimation.

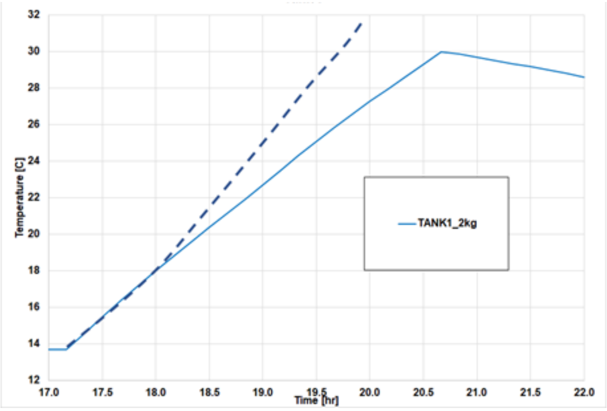

Fig.4 Comparison of trends: flight data (dash line) and simulation (solid line)

As flight data indicates, fuel in a tank with less fuel would migrate into the other tank during heating and return back during cooling. This movement between tanks could have some undesirable effect if the amount of the fuel moving out of tank will become comparable with fuel tank load. In such a case, the tank with lesser fuel can accidentally get depleted even with sufficient total fuel.

7. Conclusion

Spontanious movement of propellant between tanks can lead to errors in propellant load estimations by the Thermal Gauging Method. It also can lead to accedental depletion of the tank with lesser amount of the propellant. Incorporating dynamic fuel flow modeling is essential for accurate end-of-mission fuel estimations.

A similar problem of uneven propellant distribution in multiple tank propulsion systems can araise in different spacecrafts if tanks are connected on both sides, that is, by gas and propellant lines.

8. References

1. **"2001 Mars Odyssey Mission Summary"**
2. **"Introduction: 2001 Mars Odyssey Mission"**
3. **2001 Mars Odyssey Arrival Press Kit**
4. Collicott, S., Yendler, B., **“Asymmetric Propellant Positioning in Symmetric Tanks and Propellant Management Devices**”, Journal of Spacecraft and Rockets, October 2021, AIAA DOI: 10.2514/1.a35095
5. B. Yendler1, B; et al, “Prediction **of Spacecraft Remaining Life -Challenges and Achievements”,** AIAA-2013-4162; 2 Jul 2013
6. Brakke: K. A. Brakke, "The Surface Evolver", *Experimental Mathematics*, 1992, Vol. 1, No. 2, pp 141-165.
7. Collicott, S. H. and Weislogel, M. M., "Modeling the Operation of the VTRE Propellant Management Device", *38th AIAA Joint Propulsion Conference and Exhibit*, July 2002. AIAA-2002-4140