TOPS Attitude Propulsion Subsystem Technology

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This article summarizes the JPL Thermoelectric Outer-Planet Spacecraft (TOPS) Attitude Propulsion Subsystem effort through the end of fiscal year 1971. It includes the tradeoff rationale that went into the selection of anhydrous hydrazine as the propellant, followed by a brief description of three types of 0.445-N (100-mlbf)[1] thrusters that were purchased for in-house evaluation. A discussion is also included of the 0.2224-N (50-mlbf) JPL-developed thrusters and their integration with a portable, completely enclosed, propulsion module that was designed and developed to support the TOPS single-axis attitude control tests in the JPL Celestarium. The article concludes with a synopsis of further work which will be accomplished prior to the onset of an outer-planet mission.

Function and Description

The Thermoelectric Outer-Planet Spacecraft (TOPS) is a three-axis stabilized vehicle for which the primary attitude control and stabilization is performed by three mutually perpendicular momentum wheel sets. The wheels in each axis have been implemented as redundant pairs to increase the mission probability of success. The primary requirement of the Attitude Propulsion Subsystem (APS) is to function in support of the Attitude Control Subsystem.

The APS is required to: (1) perform tipoff rate reduction and acquisition maneuvers immediately after launch; (2) perform approximately 2500 momentum wheel unloadings in the yaw axis (less in the pitch and roll axes); (3) perform commanded turns, which consist of nine positioning maneuvers throughout the 10-yr mission to orient the spacecraft for trajectory correction, of rolling the spacecraft 60 times (once every half AU) and yawing 30 times (once every AU) for calibration of science instruments, and of performing up to 20 re-acquisitions in the event of transient excursions

[1] Values in customary units are included in parentheses after values in SI (International System) units if the customary units were used in the measurements or calculations.

outside the sensor deadband; and (4) perform backup limit cycle control in the event that 2 wheels fail in a single axis. These functions, with the exception of item (4), are summarized in Table 1 in terms of the required torque impulse. If backup limit cycle is required, the necessary propellant will be derived from the Trajectory Correction Propulsion Subsystem (TCPS) allocation. A spacecraft system-level tradeoff has determined that a net mass saving can be realized if the momentum wheel mass is reduced by transferring the functions of performing the various commanded turns to the APS.

The TOPS APS baseline configuration is integral with the TCPS, thus comprising the TOPS propulsion module. The TCPS and the APS share a common propellant supply of liquid anhydrous hydrazine, which is sized primarily by the TCPS design requirements. The APS propellant lines extend from the supply tank to the thruster/valve assemblies located in the propulsion bay and protrude through the thermal blanket. The present configuration of the TOPS propulsion module is depicted in Figure 1. The locations of the roll, pitch, and yaw thruster/valve assemblies, along with the related components, are indicated.

Table 1. TOPS APS torque impulse requirements[a]

Function	Pitch		Yaw		Roll	
	m-N-s	(ft-lbf-s)	m-N-s	(ft-lbf-s)	m-N-s	(ft-lbf-s)
Rate reduction (54 mrad/s)	21.76	(16)	110.2	(81)	110.2	(81)
Commanded turns (3 mrad/s)						
Positioning for trajectory correction (9)	—	—	220.3	(162)	220.3	(162)
Science maneuvers (60 roll, 30 yaw)	—	—	734.4	(540)	734.4	(540)
Re-acquisitions (2/yr)	48.96	(36)	244.8	(180)	244.8	(180)
Wheel unloadings						
Solar torques	122.4	(90)	613.4	(451)	97.9	(72)
Micrometeoroid	68.0	(50)	68.0	(50)	68.0	(50)
Contingency	78.9	(58)	171.2	(126)	224.5	(165)
Totals	340.0	(250)	2162.3	(1590)	1700.1	(1250)

[a] Required total impulse (based on nominal moment arms for the 3 axes) = 10,200 N-s (2295 lbf-s).

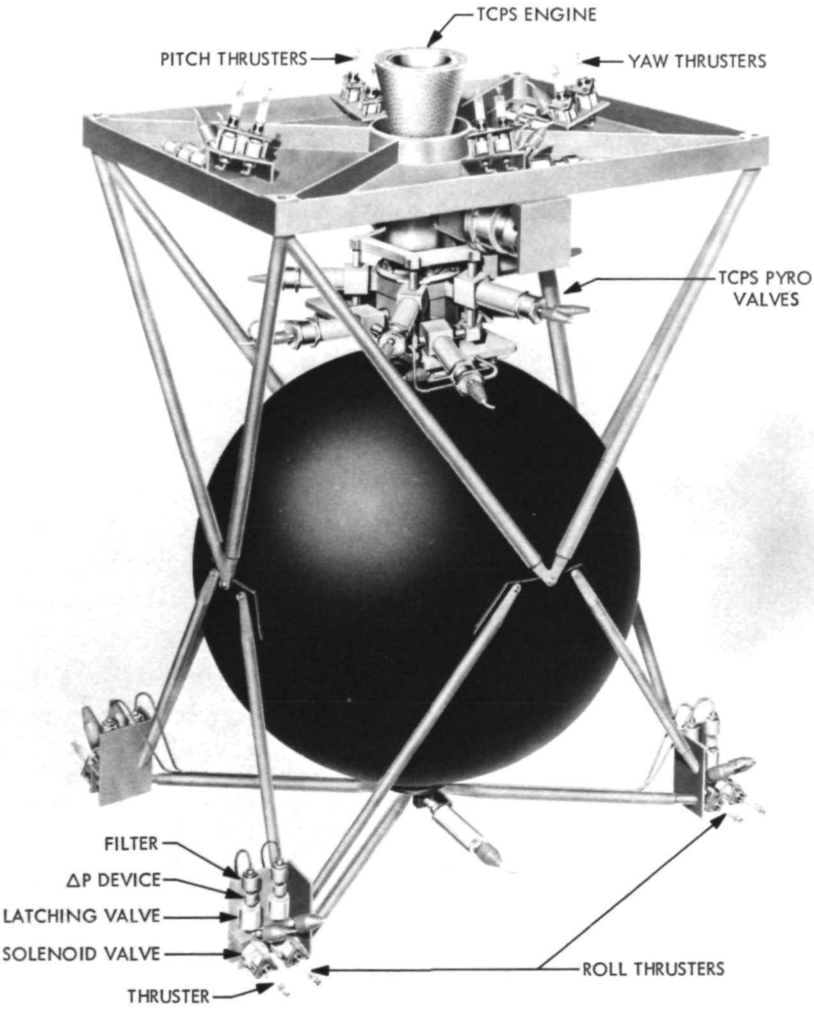

Figure 1. TOPS propulsion module configuration 12L/A

The APS consists of 16 thruster/valve assemblies, of which 8 will be active and 8 will be standby redundant. In the event of a single thruster/valve failure, the function of the failed unit will be transferred to the standby unit on a one-for-one basis. The requirement for 8 active thrusters rather than 6 is derived from the fact that the roll thrusters are implemented as a couple, while those for pitch and yaw are non-coupled. The nominal beginning-of-mission torque level requirements are 0.136 N-m (0.1 ft-lbf) in pitch and 0.27 N-m (0.2 ft-lbf) in roll and yaw. Each thruster is designed for a nominal 0.4448-N (0.1-lbf) thrust.

The single-propellant tank operates in a blowdown mode (rather than being pressure-regulated) to improve subsystem reliability. The tank pressure blows down from 2.76×10^6 to 1.38×10^6 N/m^2 (400 to 200 psia) as dictated by TCPS requirements. The APS thrusters operate at a lower inlet pressure than does the TCPS thruster, and, therefore, each APS thruster/valve combination incorporates a pressure-dropping device. The baseline device is a coiled section of small diameter tubing [approximately 0.381 m (15 in.) long by 2.54×10^{-4} m (0.01 in.) internal diameter]; however, a smaller fluid resistance device that is less susceptible to contamination is also being tested. The pressure-dropping device also serves as a means of metering the very low liquid flowrates [approximately 2.268×10^{-4} kg/s (5×10^{-4} lbm/s)].

Each APS thruster/valve assembly consists of a thruster, a thermal isolation structure and injector tube, a normally closed solenoid valve, a latching solenoid valve, the pressure-dropping/flow-metering device, and a filter. Each active thruster is injected with liquid anhydrous hydrazine, which is decomposed through a 20–30-mesh Shell 405 catalyst bed to generate hot gases that are expelled through a high-expansion-ratio nozzle. Each thruster is coupled to its solenoid valve through the thermal isolation structure to minimize heat soakback into the valve seat area.

The baseline filter is a 1-μm (absolute), stacked disc labyrinth filter. This unit, which incorporates a JPL etched disc design, was designed and fabricated by a contractor who has assembled and acceptance-tested five units. These have been delivered to JPL for further evaluation.

The baseline normally closed solenoid valve incorporates an internally actuated, in-line poppet to take advantage of the smaller mass and envelope. However, studies of the externally actuated (torque motor) concept are also being conducted. The valves incorporate a soft seat sealing configuration,and studies to determine the optimum seat design and material are being conducted.

The latching solenoid valve is similar to the normally closed solenoid valve but possesses a bi-stable actuator that enables the valve to be positioned in either an open or closed condition. The valve repositioning is executed by a short-duration electrical pulse, after which no further holding power is required.

Tradeoff Rationale

At the time when a liquid hydrazine Attitude Propulsion Subsystem was first considered for TOPS, the baseline mass expulsion system was the traditional cold gas nitrogen with 0.04448-N (0.01-lbf) thrusters located at the end of 3.048-m (10-ft) lever arms. The higher performance (I_{sp}) of a hydrazine system enabled the thrusters to be relocated within the propulsion bay. This option eliminated the requirement for thermal control of the long feed lines. It also eliminated the need for line flexures and the impact on other subsystems from thruster feed lines being threaded through them. Having the propellant source common with the TCPS supply permits increased APS reserves, and eliminates the requirement for high-pressure tankage. The combination of high system performance and the storage of a low-pressure liquid (instead of high-pressure gas) propellant resulted in a reduced subsystem mass with equivalent reliability.

Experimental Thrusters

Late in fiscal year 1970, JPL purchased 0.4448-N (0.1-lbf) thrusters from Hamilton-Standard, Marquardt, and Rocket Research for in-house evaluation. These thrusters, although similar in physical size (Figure 2), are of three different internal designs. The thrusters are currently being evaluated for a TOPS duty cycle.

In support of the TOPS single-axis attitude control validation tests in the JPL Celestarium (a stellar simulation facility), a nominal 0.2224-N (0.05-lbf) catalytic thruster was designed, fabricated, and tested in-house. Since the tests in the Celestarium were to be performed on an air-bearing table at atmospheric pressures, the thruster was designed with an expansion area ratio of 1.5. The steady-state chamber pressure is nominally 4.5×10^5 N/m^2 (65 psia). A sea-level I_{sp} of approximately 1225.7 N-s/kg (125 lbf-s/lbm) was obtained, which translates to a vacuum I_{sp} of approximately 2010.2 N-s/kg (205 lbf-s/lbm) for a nozzle with a 40:1 expansion ratio. The steady-state c^* is nominally 1188.7 m/s (3900 ft/s). A conceptual view of this thruster is presented as Figure 3.

Two of these thrusters were then integrated into a self-contained, completely enclosed, portable propulsion module (shown in Figure 4), which was tested in the Celestarium. The module is composed of a 0.3048- × 0.1524- × 0.3302-m (12- × 6- × 13-in.) sheet metal enclosure for the feed system and a 0.2286- × 0.1016- × 0.076-m (9- × 4- × 3-in.) container for the solenoid valves, capillary tubes, and thruster supports. These all-aluminum enclosures are joined by a 0.457- by 0.0381-m (18 by 1½-in.)-diameter tube which functions both as a support member and as an enclosure for the propellant feed tube. All surfaces have been black anodized for minimum light reflection during Sun sensing operations. The larger section in the figure encloses the feed system, which consists of a propellant tank containing 500 cm^3 (½ liter) of hydrazine, a 5-μm (absolute) filter, a hand-operated shutoff valve (shown between the liquid and gaseous nitrogen fill valves), and the related tubing. The smaller enclosure contains two opposing thrusters (shown protruding from each end), the solenoid valves, and the pressure-dropping/flow-metering capillary tubes. The thrusters are insulated for better performance in the atmosphere. The propulsion module is

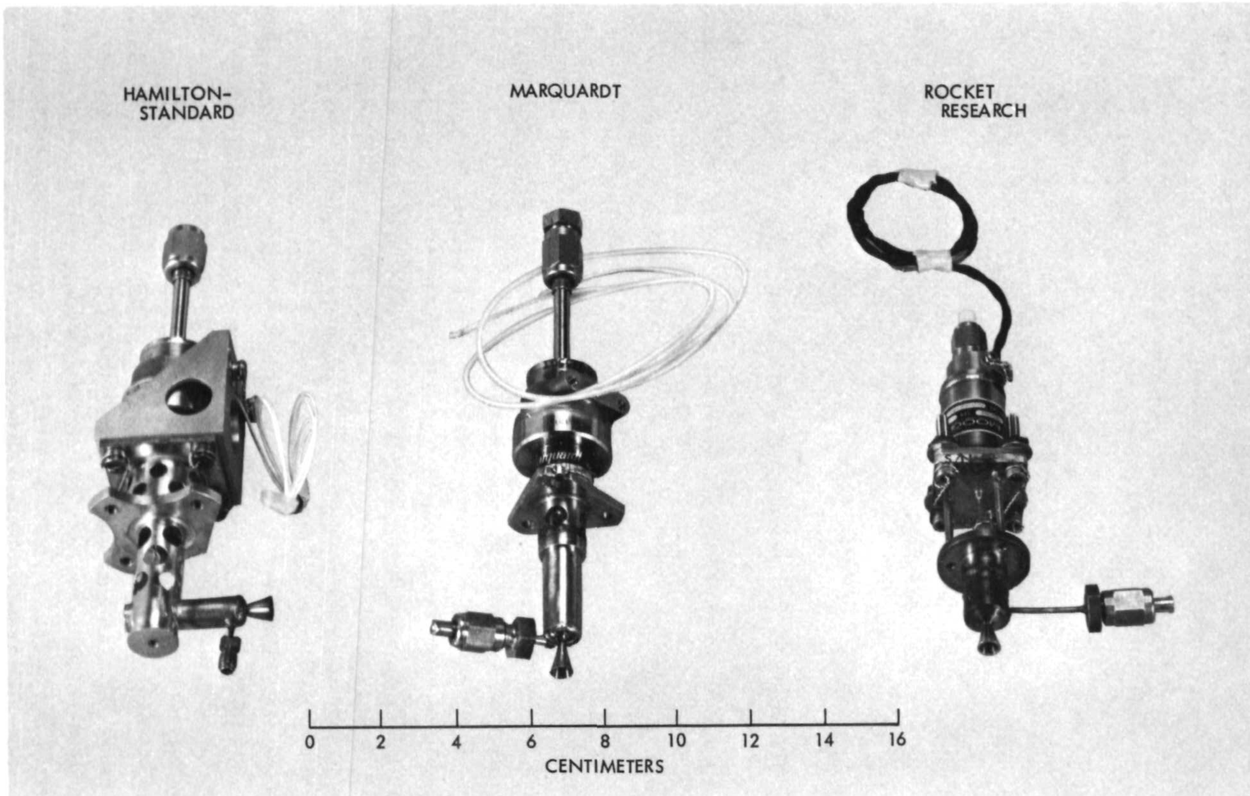

Figure 2. 0.4448-N hydrazine thrusters purchased for evaluation

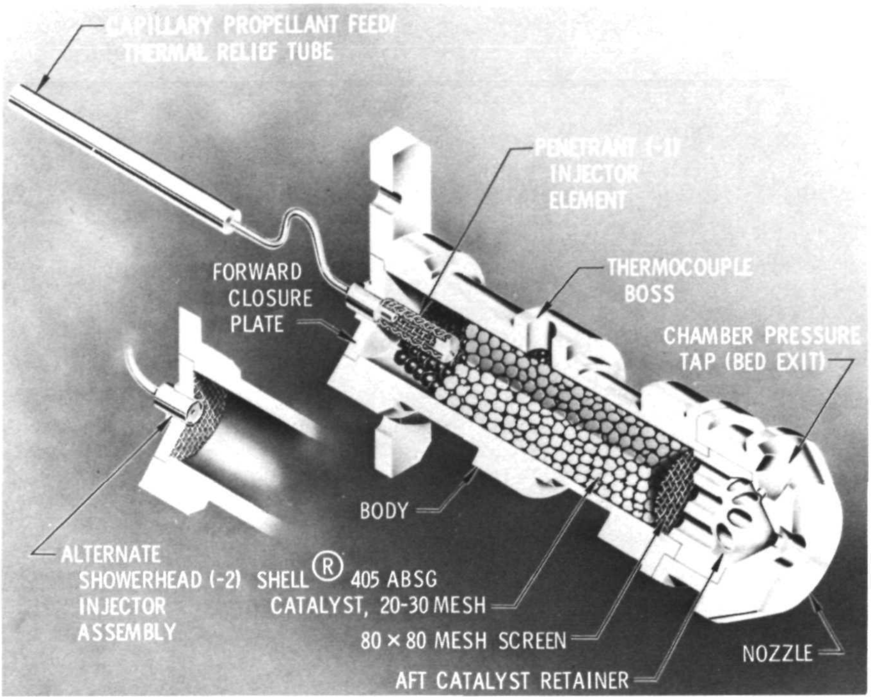

Figure 3. In-house 0.22-N (0.05-lbf) thruster design

shown assembled on the air-bearing table in the insert of Figure 4 and has been photo retouched (lightened in color) for clarity.

The feed system was assembled from components designed to sustain very high pressures. The supply tank, one of the weaker components, has been coded for a 2.758×10^7 N/m^2 (4000 psig) working pressure with a 4:1 safety factor and has been proof-tested to 4.137×10^7 N/m^2 (6000 psig). The maximum pressure to be experienced during air-bearing table tests is 2.758 $\times$ 10^6 N/m^2 (400 psig). This ample margin of safety, combined with a history of safe operation and nominally low chamber pressures, was instrumental in obtaining a "man rating" for the module so that it could be operated in the presence of personnel. This action greatly facilitated the checkouts and demonstrations of the air-bearing table.

For comparison, an additional 0.2224-N (0.05-lbf) thruster was fabricated with a shorter (0.0128-m) catalyst bed for less ammonia dissociation (55% instead of 72%) and loaded with 20–30 mesh, 90% attrited Shell 405 catalyst (nearly spherical granules). This thruster has been subjected to a series of 1532 "cold" starts [thruster and propellant temperature at a nominal 20°C (68°F) prior to each ignition]. The steady-state on-time for each cold start was approximately 10 s to allow the catalyst bed temperature to approach thermal equilibrium. This test series precipitated from the consideration

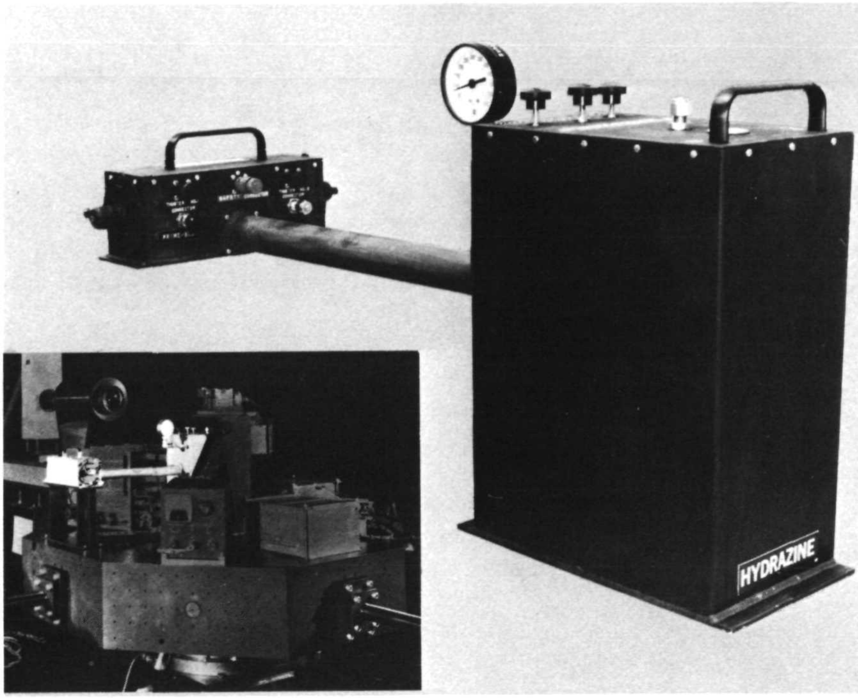

Figure 4. Celestarium propulsion module

that the propulsion bay of an outer-planet mission spacecraft would be thermally controlled between 4.45 and 32.2°C (40 and 90°F) at a nominal 20.1°C (70°F), and from the original requirement that there would be approximately 1100 starts per thruster with the thruster initially in thermal equilibrium with the propulsion bay. The number 1500 was chosen as having sufficient margin to demonstrate feasibility. The 90% attrited catalyst was chosen from data that tended to indicate that it may have the highest cold-start survival probability. (However, more recent findings indicate that, in reality, the non-attrited granules may be superior.) Since the time these tests were performed, the requirements for maximum number of starts in any one axis have increased from 1100 to approximately 2500 in yaw.

Concluding Remarks

It has been demonstrated that a liquid hydrazine Attitude Propulsion Subsystem can meet the primary TOPS mission requirements. The capability of the system to survive the life (duty cycle) requirement has been verified by vacuum chamber tests, and the system compatibility with the spacecraft dynamics has been demonstrated by the air-bearing table tests in the Celestarium.

Future Effort

The remaining TOPS APS effort will be to complete the evaluation of the purchased catalytic thrusters for a TOPS duty cycle and to publish a detailed final report on the overall APS activity. This effort is scheduled for completion by the end of 1971. An effort is underway to obtain and evaluate at least one electrothermal thruster in parallel with the TOPS effort for possible application on an outer-planet mission spacecraft. An electrothermal thruster operates on the principle that the monopropellant decomposition is initiated by an electrically induced heat source and sustains itself thereafter with no further power input.

More extensive work in the APS valve area is required and will be conducted with specific emphasis on extended life expectancy, seat design, power and envelope tradeoffs, and magnetic field definition.

The filtration requirements will be re-evaluated to ascertain an acceptable flight minimum. Further evaluation of the 1-μm (absolute) filter will be conducted to specifically address the question of the ultra-fine filtration limitations and operating problems. This effort will aid in defining realistic requirements related very closely to the propellant cleanliness definition and valve seat particle absorption capability.