Attitude Control Thrusters and Reaction Control System Engineering Report

ER Rocket Inc.
Embry-Riddle Aeronautical University
1 Aerospace Blvd
Daytona Beach, FL

Mason Dunsmuir, Andre Gomez Lopez
April 18th, 2025

I. Introduction

Precise attitude control is essential for ensuring spacecraft stability, executing trajectory corrections, and performing docking operations with the Martian space station. The Reaction Control System (RCS) provides both rotational and translational maneuvering capabilities necessary for spacecraft orientation adjustments. These controlled attitude changes are critical for thermal regulation, burn alignment, and docking precision. With a section of thrusters on the Zvezda module and two thruster packs mounted near the bottom of craft (by two fuel tanks), the rocket is able to rotate and translate to full capabilities on all axes. The maneuvers required include undocking, docking, two burn alignments, and two rotations. The first rotation will occur during assembly and the second for thermal regulation.

II. Active Center of Gravity (CoG) Monitoring System

The spacecraft's moment of inertia changes dynamically due to fuel consumption, direction of drainage, and deployment of onboard components. To maintain precise control, an active CG monitoring system continuously analyzes these shifts and transmits real-time data to the Attitude Control Thrusters (ACT). This system ensures that thrusters fire optimally and generate the required torques by adjusting the flow rate through each thruster. This is achieved by controlling the solenoid valves, minimizing unnecessary fuel and maintaining precise control, even under varying spacecraft conditions. The center of gravity is expected to fluctuate up to 8 meters above and below an origin point (defined as the central point in between the two layers of fuel tanks).

III. Thruster Positioning and Geometry

When considering the same origin point used to describe CoG fluctuations, at approximately 14 meters below this point will be where two thruster packs will be holstered for maneuvering. These thrusters will be attached onto the engine mount trusses of two liquid hydrogen tanks, separated by 180 degrees. In compliment to this geometry will be four pairs of thrusters, separated by 90 degrees, on the Zvezda module (above the IDA ports). Together, these thruster arrangements will control pitch, sway, and heave maneuvers. Roll and surge maneuvers will be done solely with the mounted thruster packs. Due to the asymmetric lever arms between the two sets of thrusters (integrated and mounted), fuel efficiency losses have been calculated (compared to symmetrical geometry). For pitching maneuvers, the ACTs operate from 57-89% efficiency (lowest to highest CoG, respectively). For sway and heave maneuvers, the ACTs operate from 14-79% efficiency (lowest to highest CoG, respectively). The two sets of thrusters are shown below in Figure 1 in a simplified structure that accentuates the positioning and orientation of the rocket’s RCS.

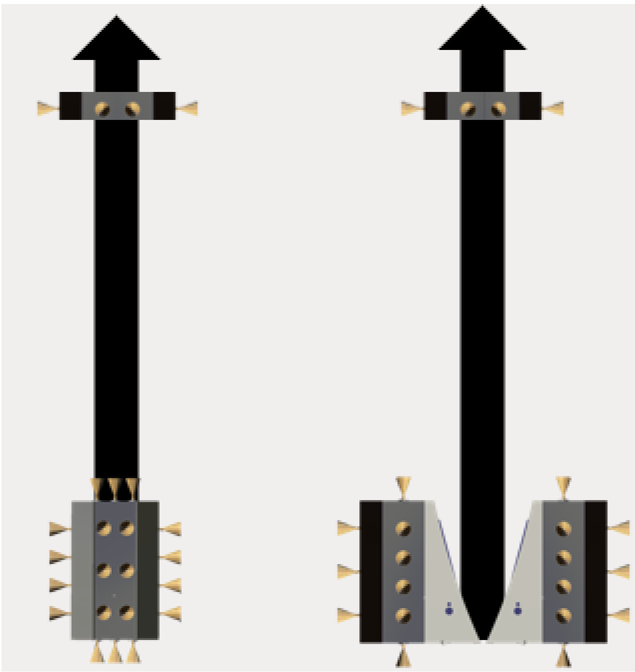

Fig. 1 Simplified Model Depicting RCS from Front and Side-Views.

IV. Thruster Selection and Fuel Usage

For attitude control, bipropellant thruster packs similar to the Ariane Group 200N model have been selected due to their reliability and high-performance characteristics. The propulsion system employs Unsymmetrical Dimethylhydrazine (UDMH) as fuel in combination with N2O4 oxidizer. This selection reduces system complexity by eliminating the need for additional tubing while ensuring compatibility with the existing spacecraft's architecture (native ACT propellant on Zvezda module). The high-energy density of UDMH, combined with its stable storage properties, makes it a suitable choice for extended mission durations in deep space. The Zvezda hosts about 60 gallons worth of propellants and each thruster has a maximum power draw of 32 Watts. No more than 32 thrusters may fire at full power at any time as it may over-draw power from that allotted to Zvezda. During nominal operations this will never be the case.

Prior to refueling requirements, the spacecraft will use the ACTs to perform an undocking and docking maneuver, taking 180 minutes and 90 minutes to perform, respectively. These maneuvers are also found to consume 72kg and 60kg of fuel (respectively) when considering the mass crafts and avg velocities of 2cm/s and 4cm/s, respectively. Additionally, the rocket will have to utilize the RCS to align prograde after departure, align retrograde for insertion, align parallel for arrival, and initiate a thermal regulation roll. Since none of these maneuvers have high time sensitivity associated with them, the remaining 118kg of propellant is found to suffice for these additional maneuvers while also having reserve propellant for any overshoots, miscalculations, or emergency maneuvers that may occur per flight.

V. Structural Materials, Justification, & Analysis

The material selection for the Reaction Control System (RCS) was based on performance under high thermal loads, mechanical stress, and mass efficiency for orbital operations. The assembly includes a niobium alloy nozzle, Inconel 625 backing, and Ti-6Al-4V housing structure. The following subsections detail each component's properties, mass, function, and rationale for selection.

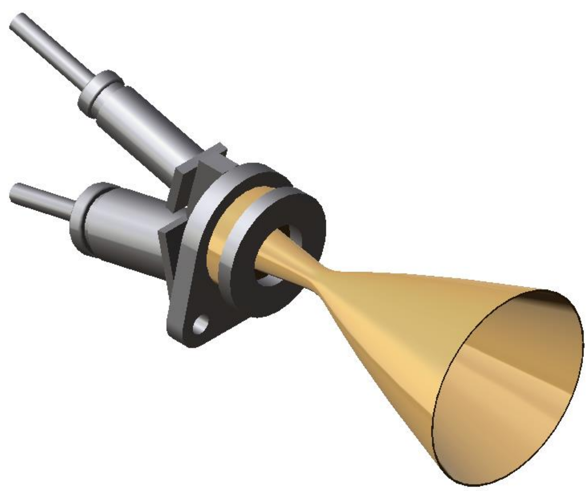

Fig. 2 200N Thruster Assembly (Nozzle Cone & Backing)

1. Nozzle Cone – Niobium Alloy

The nozzle cone is fabricated from silicon-chromium-iron-coated niobium alloy. Niobium provides exceptional resistance to oxidation and creep deformation at elevated temperatures, a necessary attribute for sustained operation in high-temperature combustion environments.

Table 1. Niobium Alloy Mechanical Properties.

Property	Value	Units
Density	8,570	kg/m³
Young's Modulus	105	GPa
Melting Point	2,468	°C
Thermal Conductivity	54	W/m·K

- **Mass:** 0.236 kg
- **Length:** 163.414 mm

- **Inlet Diameter:** 50 mm
- **Outlet Diameter:** 95 mm
- **Wall Thickness:** 12 mm

The high melting point and thermal conductivity support efficient exhaust expansion without structural degradation. The nozzle includes a coating of SiCrFe to mitigate oxidation and improve durability.

2. Nozzle Backing – Inconel 625

A backing ring composed of Inconel 625 supports the nozzle cone. Inconel alloys are known for outstanding resistance to thermal fatigue and oxidation while maintaining strength at elevated temperatures.

Table 2: Inconel 625 Mechanical Properties.

Property	Value	Units
Density	8,440	kg/m^3
Yield Strength	~690	MPa
Ultimate Tensile Strength	~830	MPa
Melting Point	1,350–1,400	°C

- **Mass:** 1.41 kg

The Inconel backing ensures the nozzle remains dimensionally stable during high-thrust operations and acts as a thermal buffer for upstream components. It was selected for its well-documented performance in man-rated propulsion systems.

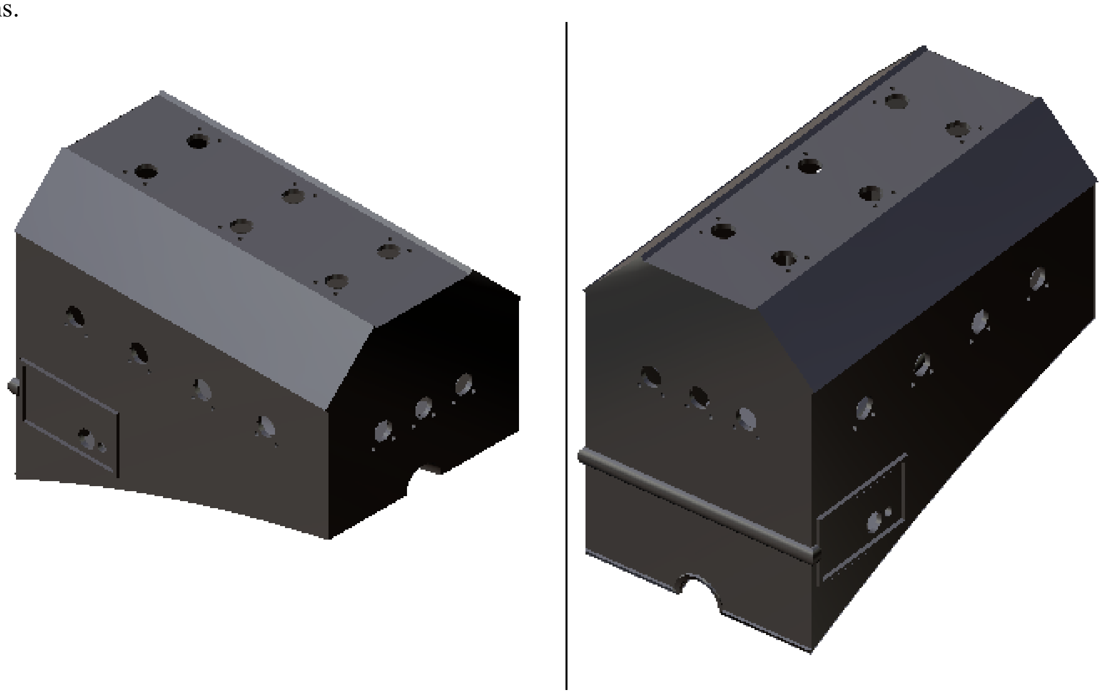

Fig. 3 Housing CAD Model

3. RCS Thruster Pack Housing – Titanium Alloy (Ti-6Al-4V)

The thruster housing and internal tank supports are composed of Ti-6Al-4V, selected for its favorable strength-to-weight ratio, corrosion resistance, and compatibility with aerospace thermal cycles.

Table 3. Titanium Alloy Mechanical Properties

Property	Value	Units
Density	4,430	kg/m³
Yield Strength	~830	MPa
Young's Modulus	113	GPa
Thermal Expansion Coeff.	8.6	µm/m·K
Melting Point	1,660	°C

- **Mass (housing + tank support):** 161.462 kg
- **Dimensions:** L: 900 mm, H: 767 mm, W: 567 mm
- **Wall Thickness:** 12 mm

Ti-6Al-4V provides robust structural support while minimizing inert mass. Its low thermal expansion reduces stress under thermal gradients during propulsion operations and orbital sunlight transitions. Minimal displacement of less than a millimeter when subjected to thermal and Newtonian loading.

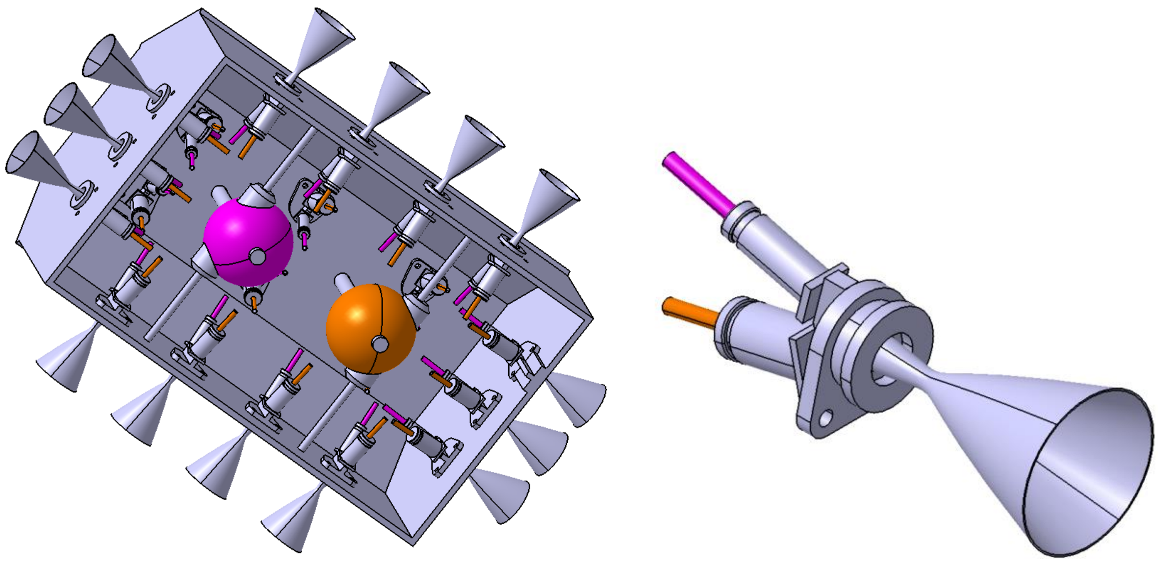

Fig. 4 Internal Assembly (Color-Coded Piping)

Each of the twenty integrated 200N thrusters is supplied by internal pressurized propellant tanks through a symmetric manifold distribution system. The magenta and orange spheres represent the oxidizer (N_2O_4) and fuel (UDMH) tanks, respectively. Dual-feed lines extend from each tank and route through isolated solenoid valves to a central manifold on each side of the thruster deck. From these manifolds, branch lines (not visible in figure) are routed to individual thruster injection assemblies, ensuring equalized flow and synchronized ignition across the system.

To minimize pressure losses and maintain flow stability, all primary lines are sized for steady-state operation at nominal flow rates (60–100 g/s) and rated for the full pressure range of 13–24 bar. Check valves and filters are integrated at each feed junction to prevent backflow and particulate contamination. The layout prioritizes uniform pipe length and minimal curvature to maintain balanced chamber pressures and ensure simultaneous thrust response.
The use of clustered solenoid valve banks allows grouped activation for attitude control logic, reducing power draw while maintaining redundancy. The internal piping is secured along structural ribs with thermally isolative brackets to mitigate conduction losses from adjacent components.

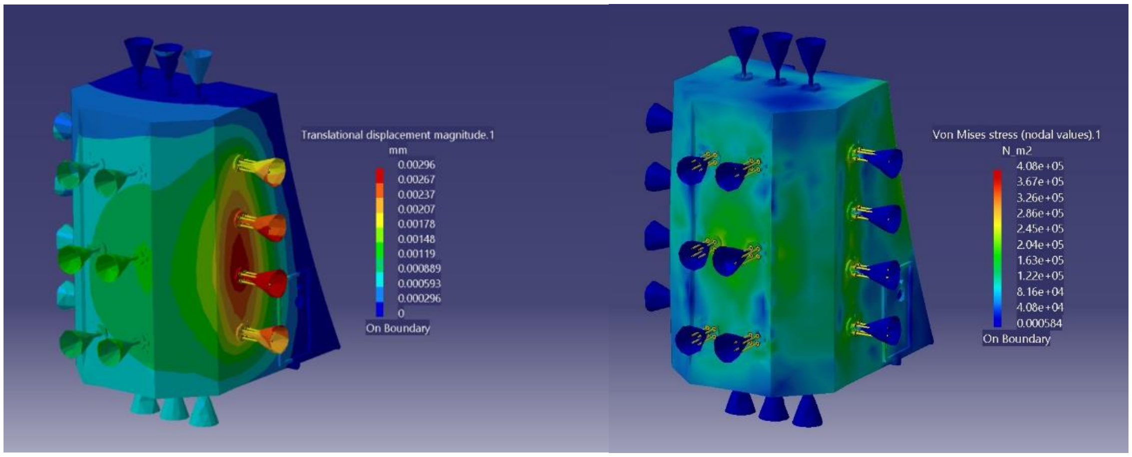

Fig. 5 Von Mises Stress analysis and Translational Displacement (Full-right Burn)

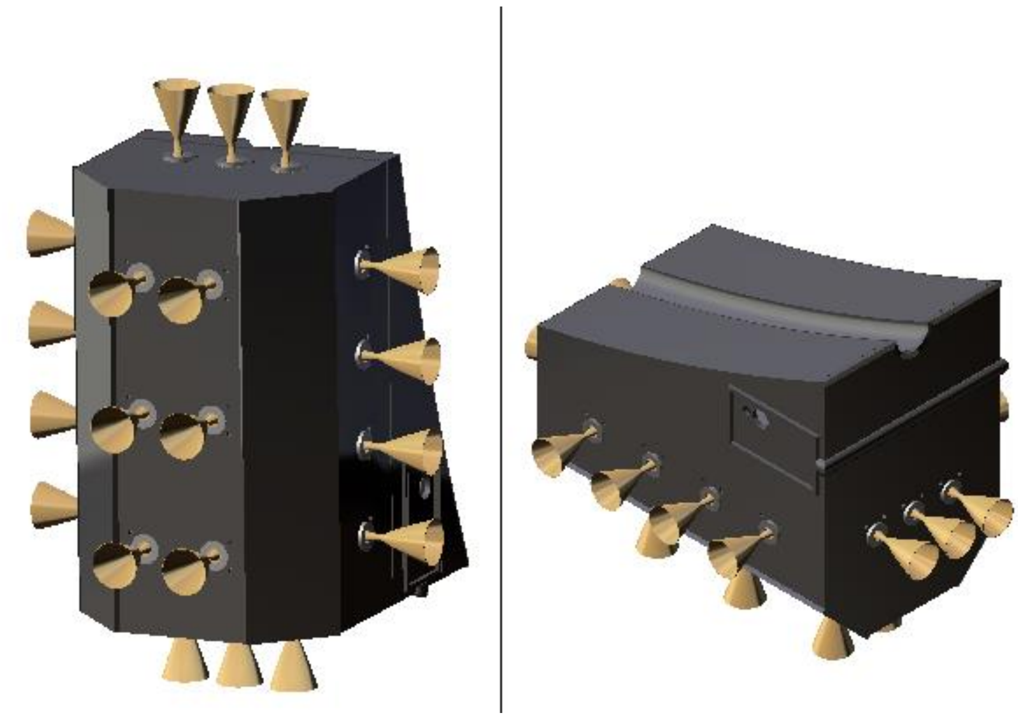

Fig. 6 Material View of RCS 20

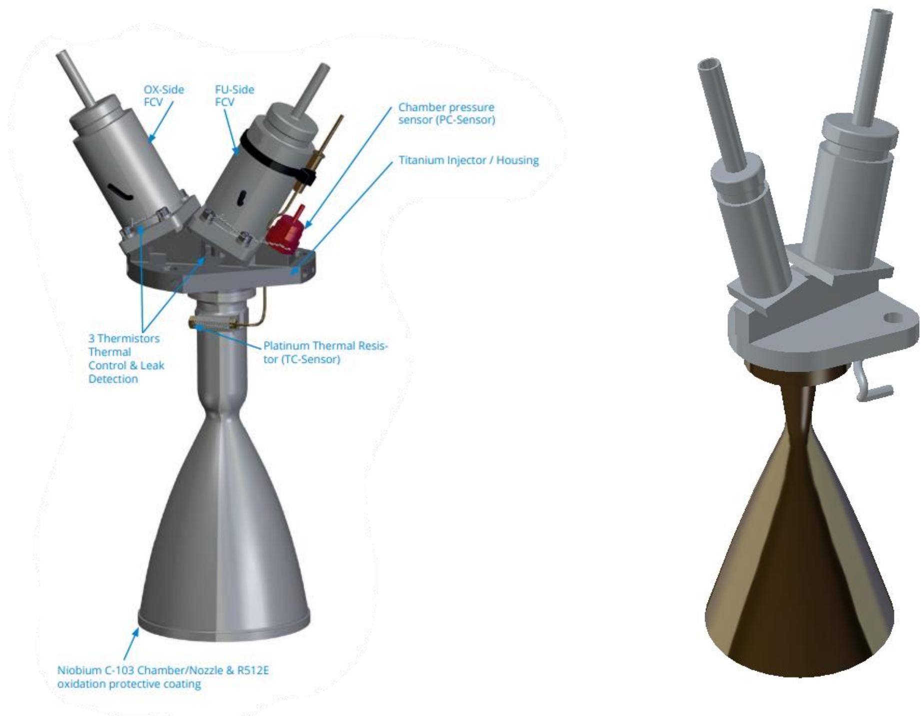

Fig. 7 Labeled View of Nozzle Assembly

The 200N bipropellant engine was developed and qualified for application as attitude control, maneuvering and braking thruster of ESA‘s ATV. The engine is designed to be capable of both steady-state and pulse mode in a very broad regimes of inlet conditions and exhibits outstanding thermal and combustion stability even at extreme conditions. To meet the specific FDIR needs of man rated missions, the engine is equipped with several flight temperature sensors for e.g. in-flight leak detection and a combustion pressure transducer [1].

VI. Thruster Performance Metrics

Specific impulse (Isp) is a critical parameter influencing RCS fuel efficiency, as it determines thrust output per unit of propellant consumed. High-Isp thrusters extend the spacecraft's operational endurance by optimizing fuel consumption while maintaining effective maneuverability. Burn time calculations ensure the system remains operational throughout all mission phases, enabling precise control during thermal regulation maneuvers, trajectory adjustments, and docking sequences. The following are figures and data for the 200N thruster:

Thrust nominal	216N ± 10N
Thrust Range	180N ± 15N to 270N ± 15N
Specific Impulse at nominal point	> 2650 Ns/Kg (>270s)
Flow rate nominal	78g/s
Flow rate range	60 to 100 g/s
Mixture ratio nominal	1.65 ± 0.035
Mixture ratio range	1.2 - 1.9
Chamber pressure nominal	8 bar
Inlet pressure range	13 - 24 bar
Minimum on time	28ms
Minimum off time	28ms

Minimum impulse bit	< 8 Ns at 28 ms
Pulse frequency	1 to 5 Hz
Throat diameter (inner)	12 mm
Nozzle end diameter (inner)	95 mm
Nozzle expansion ratio (by area)	50
Injector type	Impingement with film cooling
Mass, Thruster with valves and instrumentation	1.9 kg
Chamber / Nozzle material	SiCrFe coated niobium alloy
Fuel	MMH (qualified) / UDMH (demonstrated)
Oxidizer	MON-3 (qualified) / N2O4 (demonstrated)
Valve	Monostable dual coil solenoids, 32W
Cumulated on time	46500 s
Cumulated number of pulses	270000
Number of full thermal cycles	375
Max. t_on (single burn)	11400s

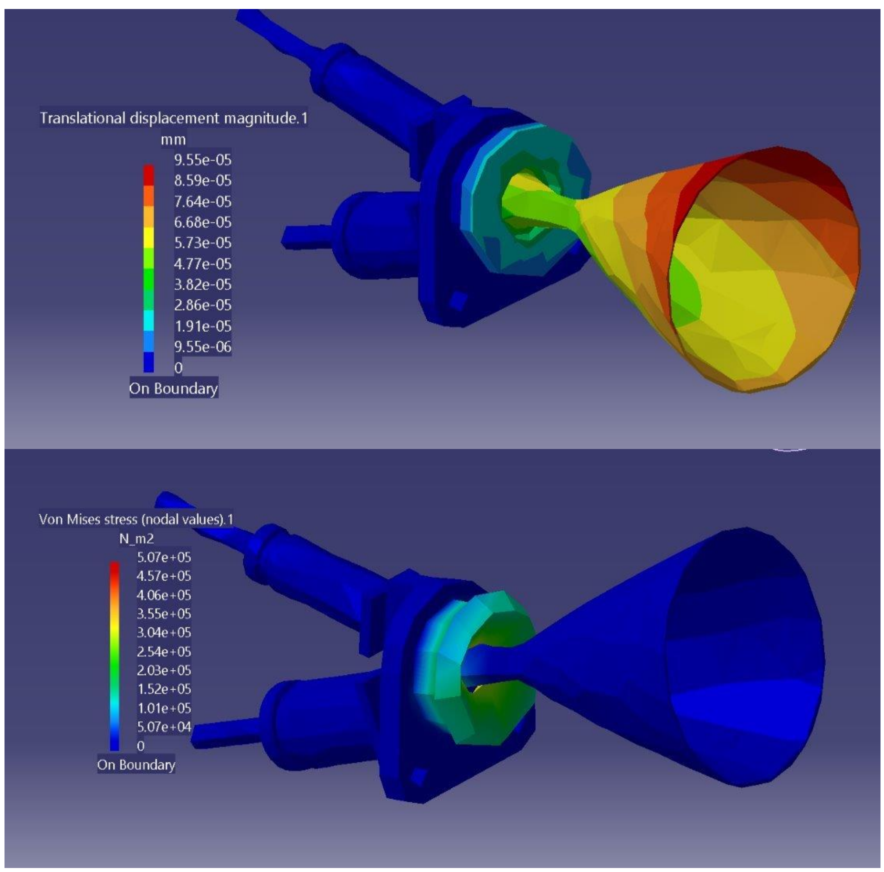

Fig. 8 Thruster data

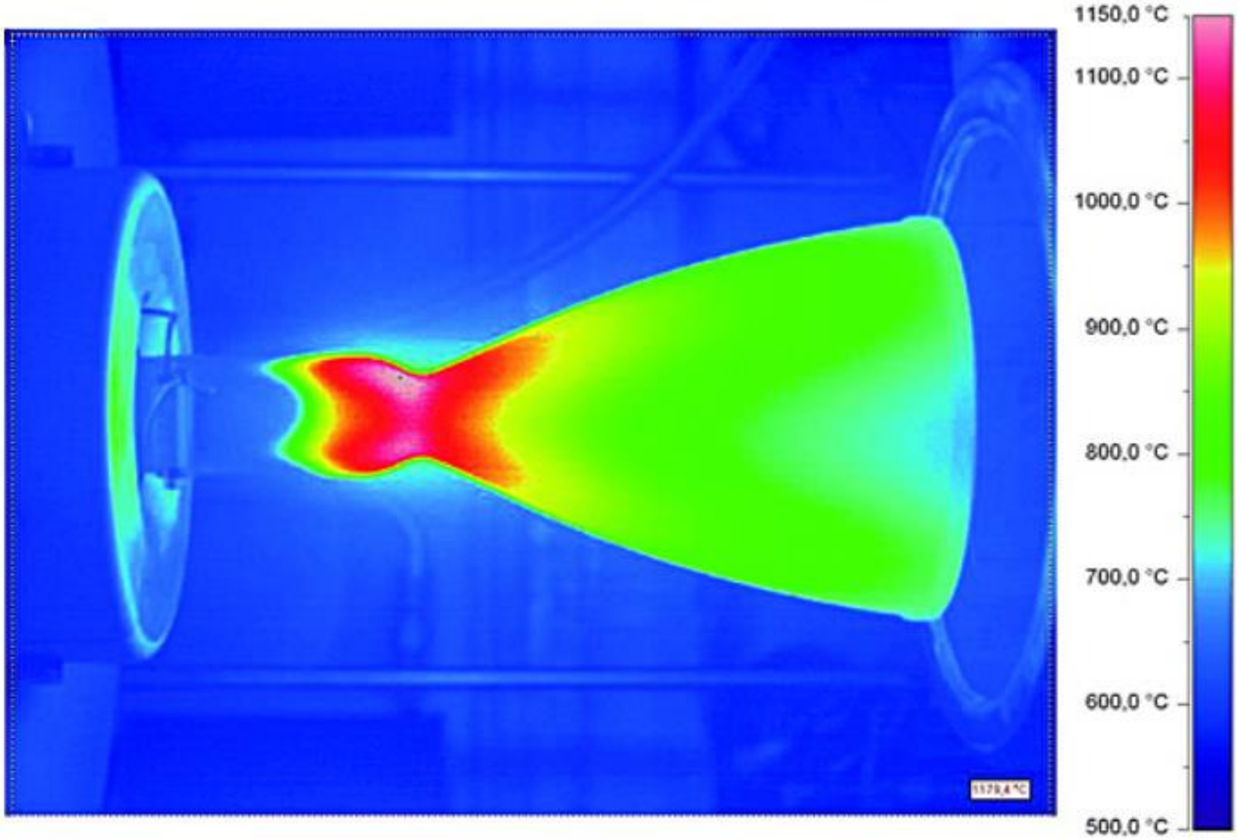

Fig. 9 IR Temperature Profile

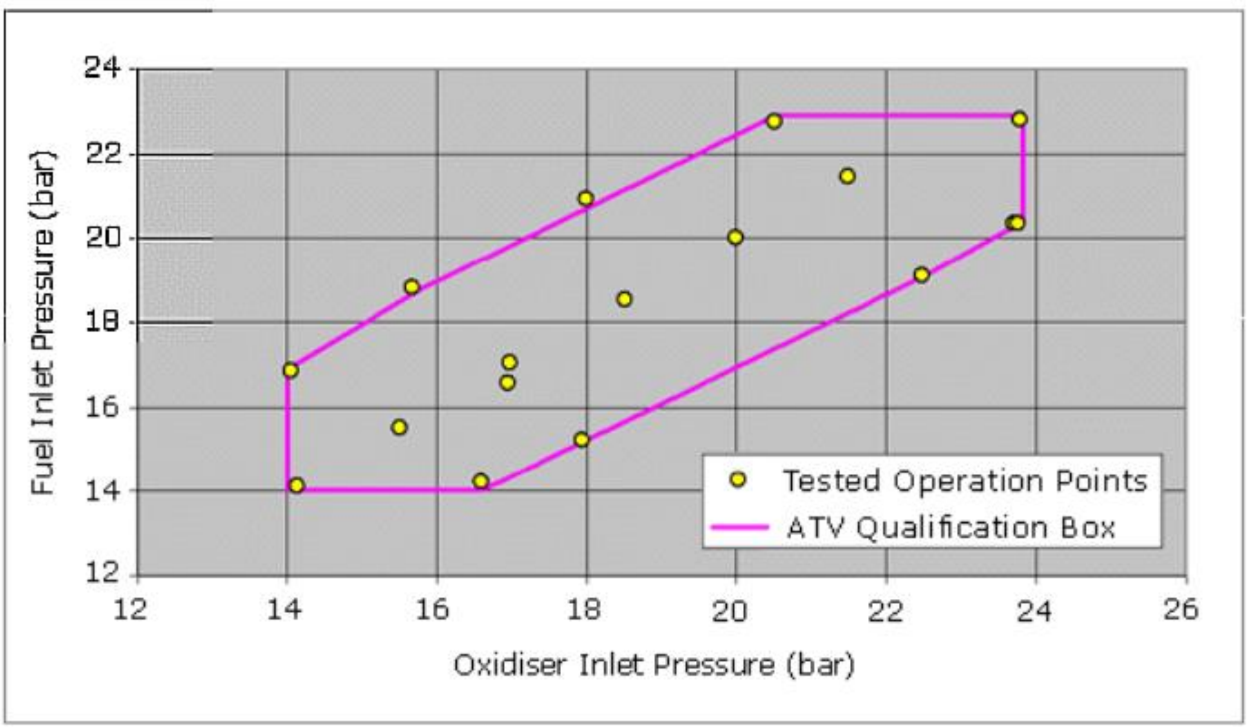

Fig. 10 Operating Box

VII. Conclusions

The spacecraft's Reaction Control System was designed to deliver precise and reliable attitude control during critical phases of the Mars mission. This includes undocking, docking, prograde and retrograde burn alignment, and thermal regulation roll maneuvers. The configuration incorporates a network of integrated thrusters on the Zvezda module and two 200N bipropellant thruster packs mounted on the engine trusses. This arrangement provides full rotational and translational control across all three axes.

Active center of gravity monitoring ensures accurate torque generation despite the expected 8-meter variation in mass distribution. The system dynamically adjusts solenoid valve flow rates to maintain stability and minimize fuel consumption. Thruster placement, evaluated relative to the spacecraft's origin point, achieves acceptable efficiency ranges for all maneuver types. Control authority remains adequate even under worst-case center of gravity shifts.

Thrusters modeled after the Ariane Group 200N bipropellant engine were selected due to their demonstrated reliability, high specific impulse, and compatibility with the Zvezda's existing architecture. The propellant selection, consisting of UDMH and N_2O_4, supports long-duration storage and deep-space reliability. Total fuel mass was validated against required delta-v profiles and maneuver times, confirming operational sufficiency with reserve capacity for contingencies.

The nozzle and housing materials were selected based on their thermal, mechanical, and mass performance. Niobium alloy nozzles ensure structural integrity under sustained high-temperature firing. Inconel 625 provides reliable thermal buffering, while Ti-6Al-4V housing maintains structural rigidity with minimal inert mass. Finite element analysis confirmed low displacement and high safety margins under operational loads.

Collectively, the rocket's RCS design demonstrates mission-readiness for long-duration Martian operations, balancing control authority, fuel efficiency, thermal resilience, and structural robustness in alignment with industry standards for aerospace vehicle design.

VIII. References

[1] Space Propulsion. "200 N Bipropellant Thruster." *Space Propulsion*, 2025, https://www.space-propulsion.com/spacecraft-propulsion/bipropellant-thrusters/200n-bipropellant-thrusters.html.

[2] Sutton, George P., and Oscar Biblarz. *Rocket Propulsion Elements*. 9th ed., Wiley, 2016.