FAILURE MODE, EFFECTS AND ANALYSIS OF AQUARIUS

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CHAVE MÓVEL

Dedication

This dissertation is dedicated to my family and friends who supported me and encouraged me through this period of my life.

Acknowledgments

It is a privilege to be able to study something I deeply admire; I am grateful for the opportunity not many have to continue their education and for those who fought for the right to make it accessible.

I would love to take the opportunity to thank and acknowledge my supervisor, Prof. Dr. Francisco Brójo, for your endless knowledge, support, and insight. I thoroughly enjoyed working with you and appreciated your wisdom whenever we talked. Thank you so much for all the encouragement and guidance, I will forever be grateful.

This dissertation is dedicated to my family and friends who supported me and encouraged me through this period of my life. Thank you for sharing your time and for listening to me, being another invaluable source of support, and for every encouragement along the way. I will try to stop speaking about satellites and thrusters from now on.

While this chapter may be closing, the lessons and experiences are forever. University shaped me in ways I never expected, and as I move to the next chapter, I am so grateful for all that happened.

Thank you all for the support!

Resumo

Neste trabalho é apresentada uma introdução ao sistema propulsivo AQUARIUS e ao seu satélite EQUULEUS, uma visão geral do uso de CubeSats e o seu impacto no setor aeroespacial, tal como a importância e inexperiência no uso de água como combustível e os seus efeitos na sua aplicabilidade. A execução do FMEA é primeiramente efetuadatendo em conta vários estudos e análises de risco e só depois são aplicadas as modificações necessárias para adaptar a um sistema aeroespacial. Com isto pretendeu-se avaliar a viabilidade e o comportamento do AQUARIUS durante a sua missão. Para isso a análise de risco foi feita a cada componente crítico do sistema.

Palavras-chave

AQUARIUS;EQUULEUS;FMEA;propulsor;água;severidade;risco;sensor;válvula

Abstract

This work presents an introduction to the propulsive system AQUARIUS and its satellite EQUULEUS; it also provides a general view of CubeSats usage and its impact on the aerospace sector, such as the importance and inexperience of the usage of water and its effects on its applicability. The execution of an FMEA is firstly analyzed, taking into consideration the number of studies and analysis conducted and only then can the modifications take place to adapt it to an aerospace system. With that it aims to access the viability and the behavior of AQUARIUS throughout the mission. For that the risk analysis are conducted in each critical component.

Keywords

AQUARIUS;EQUULEUS;FMEA;thruster;water;severity;risk;sensor;valve

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ADN	Ammonium Dinitramide
AQUARIUS	AQUA Resistojet Propulsion System
COTS	Commercial-Off-The-Shelf
DOE	Design of Experiments
DVT	Delta-V Thruster
ECSS	European Cooperation for Space Standardization
EEE	Electrical, Electronic and Electromechanical
EM	Earth-Moon
EML2	Earth-Moon Lagrangian point L2
ESA	European Space Agency
ETA	Event Tree Analysis
EQUULEUS	Equilibrium Lunar-Earth point 6U Spacecraft
FDIR	Fault Detection, Isolation and Recovery
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
HACCP	Hazard Analysis and Critical Control Points
HAZID	Hazard Identification
HAZOD	Hazard and Operability Diagnosis
LEO	Low Earth Orbit
MCDM	Multi-Criteria Decision-Making
MMOD	Micrometeoroid and Orbital Debris
NASA	National Aeronautics and Space Administration
NPR	NASA Procedural Requirements
OBC	On-Board Computer
PPU	Power Processing Unit
PVC	Polyvinyl Chloride

QFD	Quality Function Deployment
RCT	Reaction Control Thruster
RPN	Risk Priority Number
SAPs	Solar Array Paddles
SLS	Space Launch System
SPF	Single Point Failure
SWaP	Size, Weight, and Power
TCM	Trajectory Control Maneuver
TPU	Thermoplastic Polyurethane
US	United States
XTRP	X-band Transponder

Chapter 1 - Introduction

1.1 Motivation

Humans are a very curiosity driven creature, so it is no surprise that when we look up at the night sky, we dream about space and its endless possibilities. Over the years space exploration has increased rapidly. Like most of today's technology it is derived from defense and military purposes, long distance rockets were developed by Nazi Germany in the 1930s and 1940s as a long-distance weapon. Later, after the Second World War, the Soviet Union, and the United States (US) developed their own missile programs[1].

Sputnik 1 became the first artificial satellite to have been launched into Space by the Soviet Union. In 1961, Lt. Yuri Gagarin became the first human to orbit Earth in Vostok 1, which lasted for 108 minutes. During this year, the United States President, John F. Kennedy, also settled a national goal to have a man landing in the Moon and returning within a decade. This political motivation helped grow the research into space exploration, and as result of that, 8 years later the first man landed on the Moon, astronaut Neil Armstrong. "One small step for man, one giant leap for mankind" became a motto worldwide for the next generations to come. Between 1969 and 1972, there were made six Apollo missions to explore the Moon[1].

During the 1970s, there were orbiting navigation and communications satellites in the beginning for military purposes and then later to the general public. At the same time, the Mariner spacecraft was being used to map the surface of Mars. The Voyager, by the end of the decade, had sent back images of Jupiter and Saturn, their rings, and moons.

By the 1980s, satellite communications expanded to carry television signals, and the public could access those signals by their home dish antennas. Satellites were also used for exploration on our own planet, such as funding the ozone hole, pinpoint forest fires and even images of the nuclear plant disaster at Chernobyl. While astronomical satellites found new stars and a new view of the center of the galaxy.

During the Gulf War, the value of satellites in modern conflicts was proven, allied forces were able to use the satellites to provide information on enemy troop formations, movements, and others. Space systems to this day continue to be an important part in homeland defense, weather surveillance, navigation, communication, and remote sensing for disasters.

Between the late 1990s and early 2000s, due to the increased linked to Asia-Pacific demand for spacecraft and a shift from government regulated to commercial marketplace mainly for telecom satellites, there was a peak in satellite launching, being evident by the action European Space Agency (ESA) that built the 8.2 tons Envisat Earth Observation satellite, just an example among many others such as Hubble Space telescope, while on the other side of the Atlantic the National

Aeronautics and Space Administration (NASA) in collaboration with ESA and the Italian Space Agency built the 5.7 tons Cassini Planetary Exploration Mission [2].

Due to their large scale, they became a challenge to develop because of the complexity of instruments and in many cases due to the low maturity of certain technologies, micro-vibrations, and electromagnetic issues. Therefore, smaller spacecrafts became ideal with smaller instruments suites, increasing overtime [2].

Recent advances in technology miniaturization enabled the space industry to build small spacecraft from readily available, low cost, low power, and compact commercial-off-the-shelf (COTS) components [2]. Which has incentivized the use of smaller spacecrafts for educational purposes. So in 1999 the CubeSat standard (see Figure 1) was created has a collaboration between California Polytechnic State University, San Luis Obispo, and Stanford University's Space Systems Development. They were born out of the simple idea of transporting experimental very small satellites instead of dummy masses for balancing a launcher when transporting a larger satellite.

CubeSats were initially envisioned primarily as educational or technology demonstration platforms that could be developed and launched within one or two years [2]. It became the standard worldwide and is used by private companies and government organizations also[3], these devices take up a fraction of the weight of the conventional communication satellite [4].

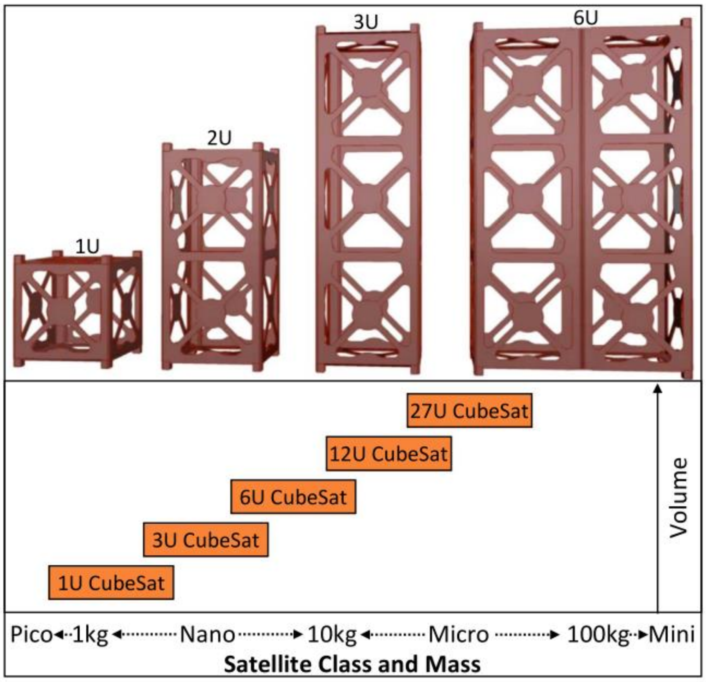


Figure 1. CubeSat specifications in the framework of overall small satellite. The volume of 1U unit equals to 10×10×10 cm^3 [2].

A 1U CubeSat could either serve as an individual satellite or could be combined to build a larger spacecraft. For example, a 3U CubeSat will have a form factor th three 1U CubeSats combined. One of the main advantages of this standardization is to allow launch vehicle producers to adopt a common deployment system independent of the CubeSat manufacturer. Given the highly successful nature of the smaller CubeSats such as 1U and 3U units, an advanced standard for larger (6U, 12U and 27U) [2].

Usually, small satellites are classified based only on their mass but in the case of CubeSat standard the volume is also considered. Table 1 gives a generally accepted classification for small satellites along with a comparison with the CubeSat standard [2].

Due to the mass and volume constraints of small satellites, the miniaturization of satellite subsystems is necessary. The complexity and range of small satellite missions has also increased, resulting in a rise in demand for in-space micro-propulsion for small satellites [5]. Since 2011, the number of nano and microsatellite launches have increased at the approximate annual rate of 40%, and it is projected that the demand for these spacecrafts will continue to show strong growth. With strong market demand for affordable space assets, there is little doubt that the number of small satellites will continue to grow [4].

Table 1. General classification of small spacecraft [4].

CLASS	MASS (Kg)
Minisatellite	100 - 180
Microsatellite	10 – 100
Nanosatellite	1 – 10
Picosatellite	0.01 – 1
Femtosatellite	0.001 – 0.01

There are different definitions of the concept micro-propulsion. Micci and Ketsdever define micro-propulsion as “any propulsion system that is applicable to a microspacecraft (mass less than 100 kg) mission”[6].

Micro-propulsion is used for attitude control, station-keeping, end-of-life deorbiting, and orbital maneuvers of small satellites. Micro-propulsion systems are utilized for a variety of applications in small satellite missions such as in-phasing maneuvers, constellation deployment, and interplanetary travel. Propulsion systems possess a considerable reputation in large spacecraft; therefore, the propulsion technologies are well-known. The miniaturization of propulsion technologies is challenging due to the limited volume available and limited power budget for propulsion systems in small satellites [5]. Monopropellant thrusters are generally utilized due to their simple design, which is less complex than a bipropellant system due to, for example fewer valves required for only one type of propellant [7].

Chemical propulsion systems, such as hydrogen or ammonium dinitramide (AND), are also commonly used for large satellites. However, thinking about the costs of toxic propellant, hardware, operation, ground support infrastructure and transportation, the valve becomes unbearable. It is difficult for a solid propellant motor to comply with safety requirements for secondary payload. Consequently, these are not feasible for small satellites [8]. For small satellites, “Green” propellants such as butane, sulfur hexafluoride, and water are used [9].

It is evident that the success of near- and deep-space microsatellite-enabled exploration relies firmly on the development of next-generation propulsion systems, the design of which should be well-matched to the specific requirements of nano- and microsatellite technologies and provide effective and dependable means for controlling their motion in space [4].
The requirements for the next micro-propulsion system are [8].

- Safety reliability, low mass, maintain performance and easy-handling for a piggy-back launch and short-span development;
- Non-high-pressure gas system for volume and weight saving (Appendix C);
- Multi functions such as delta-V maneuver or reaction control system.

One propulsion system used is the AQUA resistojet propulsion system (AQUARIUS) that has been developed since 2016. AQUARIUS uses a storable, safe, and non-toxic propellant: water. Liquid propellant storage allows for the design of all propulsion systems below 100 kPa. What is the most difficult is the high latent heat of water. To overcome this issue, the waste heat generated from communication components is reused to vaporize water. As future mission scenarios outside Earth orbit, such as the moon and Mars, lack planetary magnetic fields, magnetorquers are not capable of attitude control, and thruster-based attitude control is growing in popularity [10]. The delta-V maneuver and the reaction control system are required to AQUARIUS [8]. This includes orbit change and raising, formation flying, proximity operations, fine attitude control, drag make-up and de-orbit. These increased capabilities will allow the aerospace industry to utilize CubeSats to complete missions that otherwise would have to cost exponentially more with a standard-size satellite [7].

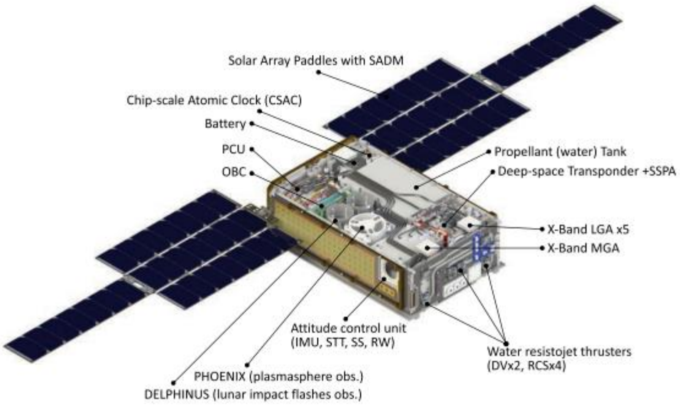


Figure 2. Internal configuration of EQUULEUS [11].

Figure 3.EQUULEUS prior to launch [12].

AQUARIUS (see Figure 4) was on board the interplanetary spacecraft: EQUULEUS, short for Equilibrium Lunar-Earth point 6U Spacecraft, which has been developed by The University of Tokyo and JAXA [13]. It was one of the ten CubeSats launched as secondary payloads aboard NASA's Artemis I mission on November 16 of 2022 [14]. It successfully completed its initial checkouts of all the bus components and executed an orbit transfer using water-propelled propulsion system in deep space for the first time [15]. The appropriate temperature and mass flow management of AQUARIUS contributed to this successful operation. Temperature control throughout the propulsion system is critical since temperature affects vapor pressure and consequently the propulsion performance. EQUULEUS has two wings of solar array paddles (SAPs), shown in Figure 2, with single axis gimbaling, generating power of 50 W in total at 1 AU. Its wet mass was 10.26 kg including a propellant mass of 1.22 kg [12]. It is notable for its focus on exploring lunar environments and Earth-Moon Systems. The primary mission was a trajectory control experiment, and its objective was to develop and demonstrate astrodynamic techniques for CubeSat missions to reach an Earth-Moon libration orbit. EQUULEUS also exploited luni-solar perturbations like others in EM-1, such as Lunar IceCube and Lunar Polae Hydrogen Mapper [11]. Soon after launch, EQUULEUS will separate from the Space Launch System and utilize lunar swing-bys to approach the Earth–Moon Lagrangian point L2 (EML2). Upon arrival, the CubeSat will insert into a EML2 quasi-halo orbit and start the scientific phase of its mission, observing lunar impact flashes with its instrument suite. During these operations, the spacecraft will also demonstrate key guidance and station-keeping technologies for future small class satellite missions to the Moon and beyond [16]. AQUARIUS, show in Figure 4; successfully conducted multiple orbital transfers including the world's first water-fueled propulsion system operation in deep space [12]. Resistojets need to be low cost, have minimal volume, and mass, and have high thermal efficiency to reduce spacecraft power requirements and comply with CubeSat constraints. They also need to simultaneously miniaturize the thruster and maintain high thermal efficiency is difficult, as reducing the thruster size subsequently reduces the heat exchanging time and flow path. Therefore, miniaturized resistojets suitable for the CubeSat platform require highly compact and efficient heat exchangers [10]. The appropriate temperature and mass flow management of AQUARIUS contributed to this successful operation.

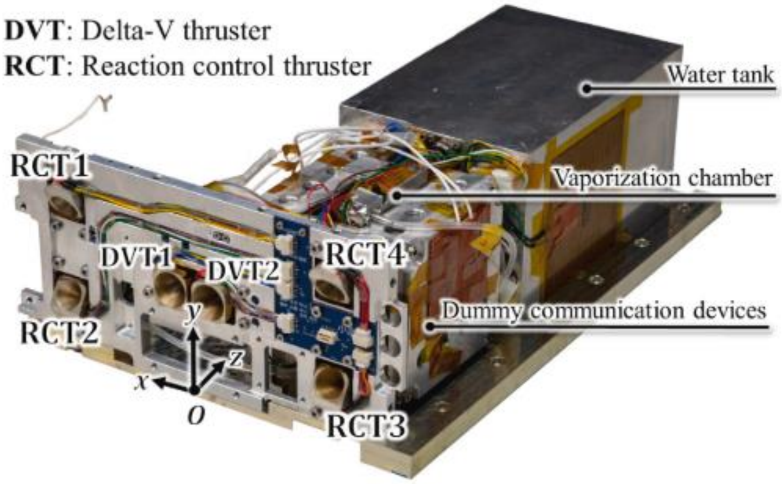


Figure 4. AQUARIUS with the x, y, z axes and the origin in the Euler coordinates [12].

1.2 Objectives

The objective of this dissertation can be divided into two groups, the general objectives, and the specific objectives that when completed can improve the results of the main objectives.

1.2.1 General Objectives

The general objectives are to define the risk factors of a micro-propulsion system and to apply them to the case study of AQUARIUS.

1.2.2 Specific Objectives

The specific objectives are to understand the risk factors (Severity, Occurrence and Detection), to understand the process of FMEA, to define the risk factors and to apply the methodology to the case of AQUARIUS.

1.3 Dissertation Structure

The work developed in this dissertation is divided into four chapters. This current chapter is constituted by the motivation and objective that lead the author to develop this dissertation theme, the objectives of the work in question and a brief history introduction.

The second chapter focuses on a literature review. Starting with risk analysis, risk factors, risk matrix and finally an FMEA analysis.

For the third chapter, it will be the analysis of the methodology used, starting with a functional description, then with the description of the application process of the FMEA on AQUARIUS, followed by its analysis of the results.

Lastly, for the fourth chapter, it will be the final conclusions and proposals for future work.

Chapter 2 – Literature Review

2.1 Risk Analysis

Safety is usually the main concern when using any space system such as a launcher, since it has stored a high amount of energy, which is needed throughout the mission. The wrongful utilization of this energy is the main risk to take in consideration from a safety standpoint, but also for other aspects like financial and programmatic ones.

The term of risk and the assessment and management of risk can be traced back to Greek and Roman times. But formal risk analysis has only begun to appear in modern times. In the 1870s, under the promotion of the U.S. Environmental Protection Agency, the role of risk assessment in management was increased, resulting in the professionalization of risk analysis. During the 1990s, research on risk also developed rapidly in various industries [17].

The concept of risk is usually associated with one well identified dreaded event to occur in a specific scenario, in which the system still manages.

In activities related to space, there is a distinction that should be emphasized:

- Collective risk, corresponding to the number of deaths anticipated during this period.
- Individual risk, corresponding to the personal risk that each individual subjected to the space transport system events.

Risk analysis consists of assessing the likelihood of an adverse event to occur that could negatively impact the project in question. This analysis is fundamental for corporations, investors, and government to assess the likelihood of a negative impact on the project after an adverse event.

For this process to be efficient, it is dependent on the availability of failure-related technical data and the form in which it is acquired. For example, sometimes only some minimal information of the system is available, so many assumptions are usually made, using comparable systems as reference. It becomes simpler when there is Failure Mode Effects and Analysis (FMEA) or alike available.

The analysis starts by identifying what could go wrong, which follows the weighing of the negatives against the probability of the likelihood of the event occurring. Finally, there is an attempt to estimate the impact caused by the event.

2.1.1 Space-Specific Risk Characteristics

Most space systems, like AQUARIUS, are exposed to challenges that do not occur in terrestrial systems. Because of a combination of damaging environmental conditions, mission criticality, and the inability to recover/repair hardware after launch, can make this analysis particularly essential in aerospace engineering. Meaning that these challenges necessitate specialized risk assessment methodologies tailored to the unique conditions of space [18].

After deployment, space systems operate in a non-serviceable domain. Most spacecraft, particularly deep-space missions like EQUULEUS, cannot be accessed for repair. As a result, risk mitigation must be built into the design from the start, with high reliability as a non-negotiable requirement, meaning that reliability needs to be built into the design [18].

The spacecraft is exposed to a variety of environmental hazards that can compromise mission success, it also exposes its systems to several hazards such as radiation, thermal cycling, vacuum effects, micrometeoroid, and orbital debris (MMOD). Radiation may degrade electronic components due to the spacecraft explosion to solar flares and cosmic rays [19]. Thermal cycling can be due to the absence of an atmosphere that can lead to mechanical fatigue and stresses, such as expansion/contraction [20]. Vacuum effects can cause material outgassing, and impact seals and thermal coatings [21]. MMOD can cause puncture tanks, damage structures, particularly critical for pressurized systems like AQUARIUS, even small particles due to high velocities [22].

A system like AQUARIUS may need to operate in a dormant state for extended periods before a brief critical activation, such as trajectory correction. Risk assessment needs to include component aging, the valve reliability after extended dormancy and material fatigue [23].

Due to certain constraints, when it comes to power and bandwidth, telemetry is sparse, especially in CubeSats. Failures might go undetected until the system is needed, which increases the uncertainty in detection metrics within FMEA [24].

Redundancy is a typical mitigation strategy in space systems, but in missions constrained by volume and mass, such as EQUULEUS, this is often limited. AQUARIUS has a single tank and a limited number of nozzles, making every component critical [11]. Redundancy increases reliability as well as derating of Electrical, Electronic and Electromechanical (EEE) components. Derating means to operate the EEE components below their maximum rated capacity [25]. This practice helps to lower the probability of failures occurring during assembly, test and flight [26].

2.1.2 Risk Classification Schemes Used by NASA and ESA

To guide the decision-making process, space agencies developed standardized risk classification systems, these are used to determine the level of risk accepted for a specific mission and to define the testing requirements, rigor, and redundancy levels for each mission.

NASA's risk-based classification system is defined in NASA Procedural Requirements (NPR) 8705.4A: “Risk Classification for NASA Payloads”. This document provides a mission assurance strategy based on a four-class system (from A to D), depending on the mission’s requirements, cost, criticality, and risk tolerance [27].

- Class A – High Priority/High Assurance;
- Class B - High Priority/High Assurance (less strict);
- Class C – Moderate Assurance/ Medium Tolerance;
- Class D – Low Assurance/ High Risk Tolerance.

Each one of these levels is not only technical assurance level but also testing depth, documentation and schedule margin required throughout the mission.

NASA, through this classification system, places CubeSat missions usually in Class D due to their high-risk tolerance, limited mission duration, limited budgets, and primary education/technology demonstration purposes [27]. But in the case, as EQUULEUS operates in deep space, a Class C might be considered, meaning higher levels of component qualification and more testing.

The ESA uses the European Cooperation for Space Standardization (ECSS) framework for risk classification and system assurance. ECSS is an initiative established to develop a coherent, single set of user-friendly standards for use in all European space activities. One of the key aspect of ECSS is the documentation architecture, which is designed to facilitate the organization and retrieval of information within the ECSS standards system. The documentation is basically organized into three main branches: Management, Product Assurance and Engineering, and four hierarchical levels. This architecture is defined to the detail level required to differentiate major functions, disciplines and activities [28]. ESA risk management is structured according to standards like ECSS-M-ST-80C (Risk Management) [29], which provide comprehensive procedures for identifying, analyzing, mitigating, and tracking risks.

ESA, instead of creating levels, relies on tailoring the risk management process to:

- The mission profile and objectives;
- The criticality of the subsystem/payload;
- The maturity of the technology used;
- The programmatic constraints.

From ESA’s perspective, the AQUARIUS subsystem would be assessed with a high severity for failure, due to its role in trajectory correction maneuvers. Given the critical role AQUARIUS plays in EQUULEUS's trajectory and navigation, the propulsion system must be treated as mission-critical, even within a Class D CubeSat. This highlights the need for early-stage risk identification, redundancy strategies, and rigorous testing.

2.1.3 Constraints in Performing Risk Analysis of Microsatellites

Microsatellite missions, particularly deep space CubeSats like EQUULEUS, represent relatively new mission classes. The restricted number of similar precedents means that statistical data on failure rates, subsystem behavior, and environmental responses are often insufficient to support probabilistic risk assessments [30]. Which increases the reliability on qualitative methods and expert judgement, adding subjectivity to the process.

These missions are often developed under tight budget and tight timelines, particularly in academic/exploratory missions. These limitations restrict the ability to perform exhaustive testing and simulations that would be standard for larger spacecraft. It can cause the risk identification to be incomplete and offers lower confidence levels in assessments [5].

The deep-space environment, such as cis-lunar space for EQUULEUS, introduces highly dynamic thermal and radiation conditions. However, most CubeSat development tools and risk models are optimized for low Earth orbit (LEO). It underestimates the risks from space weather, radiation change and thermal differences [31].

Risk assessments typically consider system resilience, including fault detection, isolation, and recovery (FDIR). CubeSats, in general, lack these due to SWaP constraints (Size, Weight, and Power), which limit the risk mitigation options that can be modeled in the analysis. Which can lead to overly optimistic assessments if it is assumed that recovery systems exist where they do not [32].

These types of missions often involve iterative development, particularly in academia, where the design may evolve during development. Lack of standardized subsystems and heritage parts further complicates formal risk modeling because they increase uncertainty in risk models and limit their reusability/validation [33].

Bases like ECSS-Q-ST-30c are designed for large-scale missions with full lifecycle planning and redundancy. This standard focuses on dependability, meaning that it ensures that a space mission is reliable and performs accordingly over time. Covering everything from Design, Development, Testing, Launch, Operation and Decommissioning. Applying these frameworks to CubeSats like EQUULEUS requires significant adaptation, which tends to lead to incompatibility/over-complexity resulting in reliance on informal risk approaches [34]. For example, redundancy tends to be overlooked in order to save on cost and on weight in a CubeSat; on the other hand, missions that use this standard to cannot forgo redundancy, having a backup is essential for these crucial missions.

2.2 FMEA Analysis

Failure Mode, Effects and Analysis (FMEA) was developed as a proper methodology in the 1960s by the US military. As for today, it has become widely used to help assure safety and reliability of products in multiple industries [35].

A failure mode and effect analysis (FMEA) is an engineering technique used to define, identify, and eliminate known and/or potential failures, problems, errors, and so on from the system, design, process, and/or service before they reach the customer (Omdahl 1988; ASQC 1983) [36].

The FMEA identifies corrective measures required to avoid failures from reaching the customer, thereby assuring the highest durability, quality, and reliability of a product or service.

A well performed FMEA allows to [36] :

- Identify potential failure modes;
- Identify the cause and effect of each failure mode;
- Identify failure modes based on the RPN;

- Corrective actions.

Performing this analysis helps evaluate the system behavior for every potential failure mode of every system component. When unacceptable failure effects do occur, changes must be made to eliminate or mitigate their causes. The critical aspect of the analysis is that the failures can be fixed based on the probability of the item failure mode and the severity of its effects [37] .

For this analysis, the procedure focuses on the characteristics of the product/service in question, also known as key characteristics. These measurement indicators help to provide feedback on the process and a quick corrective response if necessary. They also help determine the problem at the source.

In this process of the FMEA, there are used three types of key characteristics [36] :

- Leading Characteristic: a quality that can be measured and analyzed before the finishing of the product/service;
- Intermediate Characteristic: a quality that can be measured and analyzed after the finishing of the product/service, but prior to being used by the customer;
- Lagging Characteristic: a quality that can be measured and analyzed the customer satisfaction, long after the use of the product/service;

An FMEA program should start when there are new updates on the product/service, when there are new changes regardless of the reason, when there are new applications for the product/service and when there are considered improvements [36].

After the process begins, it never really ends because it becomes a living document for constant improvement, because regardless of the beginning, it will continue to use information to improve the product/service. It is updated, as necessary.

For an FMEA to be considered finished, all the hardware must have been defined, and the design must be declared frozen. The FMEA design can be considered finished when there is a release date of production, while the process FMEA may be considered finished when all the operations are identified and evaluated. The service FMEA must be considered finished when the design of the system and tasks have been defined.

Even when finished, an FMEA can be open, at any point, for a review, evaluation, and/or improvement of the product/service.

To perform an FMEA effectively one must follow a systematic approach. For that reason, there is an eight-step procedure that facilitates the FMEA [36] :

1. Selection of the team and brainstorming: The team in question must be multidisciplined and members must be willing to participate. After, it is important to prioritize the opportunities for improvement;
2. Functional block diagram/process flowchart: The functional block diagram is used for system and design FMEAs. While the process flowchart is used for process and service FMEAs. Both tools also provide an overview and a working model of the relationships

and interactions of the systems, components, and/or services and help in the understanding of the product/service;

3. Prioritize: After the team understands the problem, the actual analysis begins. Sometimes, this step is completely bypassed because of prioritization. The customer has identified the priority, or due to warranty cost or some other input, the decision has been made by the management to begin at a given time;
4. Data collection: The team begins to collect data of the failures and organizes it accordingly. At this point, the FMEA form is starting to get filled. These failures are the failure modes of the FMEA;
5. Analysis: The data is now applied for a resolution. The knowledge contributes to the decision. The analysis may be quantitative or qualitative. The team opts to use brainstorming, QFD, DOE, cause-and-effect, another FMEA and anything that the team finds useful. The information discovered will be used to fill in the columns of the FMEA;
6. Results: Based on the analysis, results are obtained. This new information will be used to quantify severity, occurrence, detection, and RPN. More columns will be filled on the FMEA;
7. Evaluate/Confirm: Now, it is time to evaluate and confirm the success or failure. After, the information from this step helps recommend the follow up actions and see the results of those actions in the columns of the FMEA form;
8. Re do it: Despite how well the step 7 went, the team must try to pursue improvement all over again. The long-term goal is to eliminate every single failure, while the short-term goal is to minimize them.

Over the years, there have been accepted four types of FMEAs. Which are [36] :

- System FMEA: Analyses systems and subsystems in the initial stages and design stage. It focuses on potential failure modes caused by system deficiencies. It also includes interactions between systems and their elements;
- Design FMEA: Analyses products before their release from manufacturing. Also focusing on failure modes caused by design deficiencies;
- Process FMEA: Analyses the manufacturing and its processes. While focusing on failure modes caused by process deficiencies;
- Service FMEA: Analyses services before delivering to the customer. It also focuses on failure modes caused by process deficiencies;

Hazard Identification (HAZID), Hazard and Operability Diagnosis (HAZOD), and FMEA are effective risk analysis methods, but only FMEA quantitatively prioritizes the risk from high to low, which can allow managers to take risk prevention and control measures [38].

2.2.1 Adaptations of FMEA for Space Systems: Application to AQUARIUS

FMEA is a commonly used method for assessing the risk of complex systems. However, when applying FMEA to space systems such as the AQUARIUS system onboard the EQUULEUS, several adaptations are necessary to address the constraints and challenges of space operations.

In the space environment, conventional FMEA must be extended to account for factors such as radiation effects, thermal cycling, and micrometeoroid impacts [39]. These environmental stressors introduce new failure modes that are not normally encountered in terrestrial systems. For Aquarius, specific attention must be given to the effects of vacuum and thermal variations on thruster valves, propellant storage, and actuator components.

Due to the limited availability of historical failure data, the FMEA for AQUARIUS must rely heavily on heritage data from similar propulsion systems, engineering judgement, and extensive case study reports and simulations [30].

Additionally, the risk priority criteria are altered to emphasize severity over occurrence. In small spacecraft with minimal redundancy, low-probability but high-severity failures must be mitigated as aggressively as more frequent, lower-severity issues [40]. In AQUARIUS, failure modes that could cause loss of thrust control or inability to perform trajectory corrections are treated with the highest criticality.

Lastly, considering the compact integration of hardware and software in small satellites, the adapted FMEA must carefully analyze software-related failure modes, such as incorrect thrust commands, loss of control algorithms, or telemetry misinterpretations [41] . For Aquarius, robust fault detection, isolation, and recovery functions are incorporated into the software to mitigate such risks.

All these adaptations enable a more realistic and mission-focused risk analysis, ensuring that critical failure paths are identified and mitigated helping to achieve/complete the EQUULEUS mission.

2.2.2 Comparison with Related Risk Assessment Methods

Other various risk assessment methodologies are regularly employed for space systems. Evaluating these techniques provides insight into their advantages and their applicability to AQUARIUS' risk management approach.

Fault Tree Analysis (FTA) is a deductive method used to determine the root causes of system failures by mapping them through logical relationships. FTA starts from a high-level event and works backward to detect contributing causes, unlike FMEA, which begins at the component level and analyzes each possible failure mode independently [42]. FTA is highly valuable for understanding complex failure combinations but requires a thorough understanding of system interactions and is typically more resource-intensive than FMEA [43].

Event Tree Analysis (ETA) operates through an inductive process, starting from a single initiating event and exploring every possible subsequent outcome, whether successful or failed [44]. ETA can model sequences of events following failure, but it does not prioritize failure modes by severity/probability as thoroughly as FMEA does.

Markov Analysis provides a probabilistic model for systems where shifts between different states (e.g., working, failed) are managed by fixed probabilities [45]. It is particularly suitable for systems with time-dependent behaviors, such as degradation in propulsion systems. However, the complexity of Markov models grows rapidly with the number of states, making them less practical for early-stage risk assessment of CubeSat-scale missions [46].

Hazard Analysis and Critical Control Points (HACCP), though originally developed for food and chemical industries, has been tailored for aerospace applications in structured hazard identification and control strategies [47]. HACCP focuses on prevention of hazards rather than analyzing failures afterwards, complementing but not replacing the systematic evaluation of failure modes provided by FMEA [48].

2.3 Risk Factors

The prioritization of risk of failure modes are based on their Risk Priority Number, RPN, which is the product of three risk factors: occurrence, severity, and detection. The RPN method is commonly used for automotive production, because it uses linguistic terminology to rank the probability of the failure-mode occurrence, the severity of its failure effect and the probability of the failure being detected on a scale from 1 to 10 which results in RPN values ranging from 1 to 1000. These rankings in question are then multiplied to give the RPN. When failure modes have a high RPN it is presumed that it is more important and it is given a higher priority than those with a lower RPN [11, 14].

RPN is obtained based on three factors [49] :

- Severity (S): Expresses the seriousness of the problem if it happens, with a focus on the consequences. The higher the number, the greater the severity;
- Occurrence (O): Expresses the likeability of the issue to occur. To determine the rate of occurrence, it is important to look at all the potential causes of a failure and the chances of those causes occurring. The higher the number, the greater the probability of occurrence;
- Detection (D): Expresses how difficult it is to identify the problem. The higher rating means an issue is less likely to be detected during test phases of development or after release. Which means, the higher the number, the less likely the failure is to be detected.

There are numerous ways to define the value of these components. The most common is to use numerical scales, also known as risk criteria guidelines. These guidelines can be qualitative and/or quantitative.

When a guideline is qualitative, there must be a follow theoretical behavior of the component. In the case of the occurrence, for example, the expected behavior is normality. In case of severity, the expected behavior is lognormal.

When the guideline is quantitative, it needs to be specific. It needs to rely on actual data, such as statistical process control, historical or surrogate data for the evaluation. The guideline does not have to follow the theoretical behavior, if it does, it is a coincidence.

After the RPN, the evaluation begins based on the assessment of the risk. This risk is defined as minor, moderate, high, and critical. It may change depending on the situation:

- Minor Risk: no action is taken;
- Moderate Risk: some action may occur;
- High Risk: definite action will take place;
- Critical Risk: definite action will take place and require extensive changes.

In case of having more than two failures with the same RPN, the first to be addressed is the one with high severity and then detection. First severity because it deals with the effects of the failure. While detection is used over the occurrence because it is dependent on the customers.

2.3.1 Criticism of Traditional Risk Priority Number (RPN)

Within traditional FMEA, the RPN has been extensively used to prioritize failure modes according to the product of three factors: Severity, Occurrence, and Detection. Despite its general use, particularly in early system development, conventional RPN presents several significant limitations, especially when applied to intricate and high-risk environments such as the AQUARIUS [50].

RPN assumes an equal weighting between severity, occurrence, and detection factors, which may not reflect operational realities for decisive space systems. In the context of AQUARIUS, a failure with catastrophic severity must be given higher priority even if its occurrence probability is low. Traditional RPN, however, may mask this distinction, leading to a risk of underestimating critical but low-probability failure modes [51].

Also, the multiplicative nature of RPN results in non-unique values: different combinations of S, O, and D can create identical RPNs, yet correspond to very distinct risk profiles [52]. For example, a highly severe propulsion failure with low occurrence can be assigned the same RPN as a moderate severity failure with frequent occurrence, despite having radically different mission consequences for AQUARIUS.

Furthermore, traditional RPN does not account for interdependence among failure modes. In AQUARIUS, interactions between the propulsion system, thermal subsystems, and avionics are complex and can lead to cascading failures. The standard RPN approach lacks the capability to model such system-level effects, further reducing its applicability for integrated space systems [53].

Due to these limitations, modifications such as weighted FMEA, fuzzy logic-based FMEA, and multi-criteria decision-making (MCDM) techniques have been proposed to enhance risk prioritization accuracy [54]. For the AQUARIUS, such improved approaches are essential to capture the nuanced risk landscape and ensure the robustness of the propulsion system during its mission lifecycle.

2.4 Risk Matrix

In 1995, the US Air Force implemented and extensively utilized the risk matrix assessment method in the life cycle risk assessment of the acquisition project for the first time. Since 1996, many projects have adopted the risk matrix method to assess project risks. The risk matrix does not have a completely fixed form, which gives subjectivity to the decision-makers [55]. A similar matrix was also used on ECSS-M-ST-80 [29].

A risk matrix is used to view the overall system risk, it is usually a colorful graph. It provides a helpful visual overview of the RNPs across the FMEA [56]. Usually, the risk matrix consists of a graph of Severity vs Occurrence values in a grid. Within each element in the grid, the number of failure modes in that group is designated.

The risk matrix color codes the risk levels, typically in green, yellow and red. Typically, the failures in green are low risk (acceptable), which means no action is required. The failures in yellow are a medium level risk, meaning there are some actions that could be minimized. But failures in the red are high and there are unacceptable risks that must be addressed immediately. The color levels are subjective to the situation[49].

A risk matrix can be described as a grading function [17] :

$$R = f(p, c) = \left[R_{ij}\right], when \begin{cases} p_i \leq p < p_{i+1} \\ c_i \leq c < c_{i+1} \end{cases} \tag{2.1}$$

Where:

- R_{ij} represents the risk ranking corresponding to the i-th level of risk probability and the j-th level of risk consequence in the risk matrix;
- p_i and l_i represents the lower limit of the i-th level of risk probability and the j-th level of risk loss, respectively;
- p_{i+1} and c_{i+1} respectively correspond to the upper limit.

A risk matrix includes three aspects: the category of consequence and probability, the number of ratings the risk matrix totally has, and the mapping of a risk rating with the combination of a consequence and a probability. The three aspects correspond to the use of the risk matrix. Table 2 shows a typical risk matrix [17].

Table 2. A typical risk matrix.

Probability Level	Consequences Level			
	1	2	3	4
1	Negligible	Negligible	Receivability	Receivability
2	Negligible	Negligible	Receivability	Reasonable Control
3	Receivability	Receivability	Reasonable Control	Strict Control
4	Receivability	Reasonable Control	Strict Control	Unacceptable

The risk matrix method is widely used as a convenient and efficient risk evaluation tool in many fields. The structure of the risk matrix is relatively simple, as shown in Figure 5. As shown, there are two axes, the horizontal axis, and the vertical axis. The horizontal axis shows the severity of the risk consequences. While the vertical one represents the probability of risk occurrence[17].

Both axes are divided into intervals according to the desired ratio. The intersection of each row and column interval becomes the smallest unit of the risk matrix, also known as the cell of the risk matrix.

Most commonly, it has M x N cells, being M the categories of consequence and N the categories of likelihood.

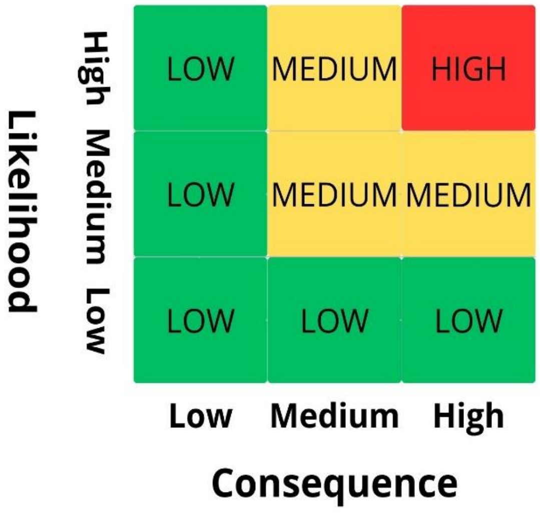


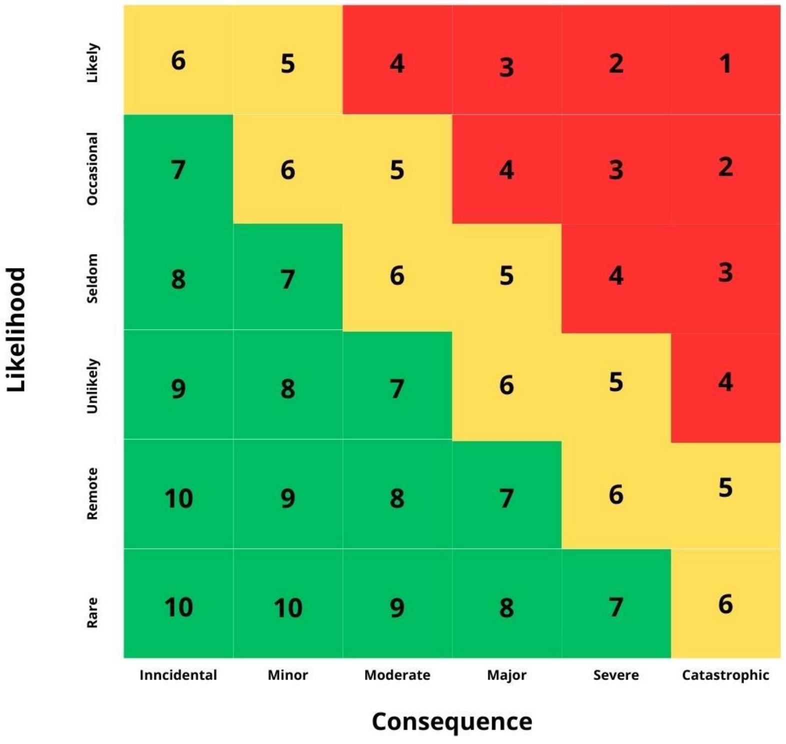
Figure 5. A 3 x 3 risk matrix.

The risk matrices in Figure 6 and Figure 7 are typical qualitative ones.

When using a qualitative risk matrix, one should first examine the categories of the assessed risk consequences and likelihood, and then the recommended risk matrix provides the risk rating. In a qualitative risk matrix, there is no explicit risk measure [17].

For qualitative risk matrices, most people choose some design rules from practice: cells along a diagonal with the same slope have the same risk and bordering risks are classified the same rating. If the above rule works, it means some arrangements of qualitative descriptions of risk criteria have the same degree of risk and it is probable that risk is measured by the formula "risk = consequence + likelihood".

By the cell rule, cells on adjacent diagonals can be categorized together. The risk matrix was rated by Pritchard et al. to assess the risk of drilling hazards and numerical representation of the risk properties.



	Inncidental	Minor	Moderate	Major	Severe	Catastrophic
Likely	6	5	4	3	2	1
Occasional	7	6	5	4	3	2
Seldom	8	7	6	5	4	3
Unlikely	9	8	7	6	5	4
Remote	10	9	8	7	6	5
Rare	10	10	9	8	7	6

Figure 6. The matrix designed by Pritchard et al.

In the case of quantitative risk matrices, it is possible that assigning multiple thresholds of risk contours corresponding to numerical values, which may divide a cell in two or even more areas, Ruan et al. adopted the area approach to determine the eventual rank of a cell [17].

As shown in Figure 7, two risk contours separate a 3 × 3 risk matrix into three ranks, thus determining the eventual rank assigned to each cell. Other more systematic design approaches are also available.

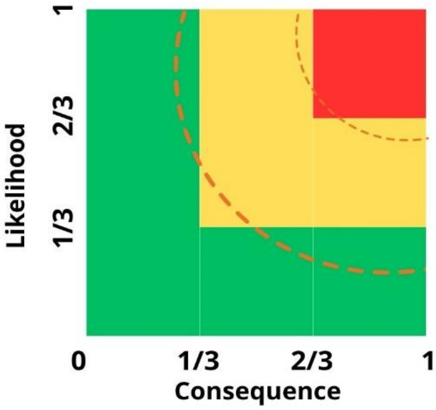


Figure 7. Risk matrix as rated by Ruan et al.

Chapter 3 – Methodology and Analysis

3.1 Functional Description

Several water-based propulsion systems have been proposed over the years, such as water ion thrusters, water Hall thrusters, water radio-frequency electrothermal thrusters, water-fueled magnetron sputtering propulsion, and water electrolysis propulsion [15], but none of them compare to the water resistojet thrusters in terms of how straightforward the thrust generation principle is. Thrusters are the primary actuators to perform orbit control because they maintain orbital energy, counteracting drag; they correct the orbital trajectory, namely eccentricity, they adjust orbital longitudinal separation for constellations of satellites; they actively control formation flying of multiple satellites; they perform change of orbit, including deorbiting. Because of their inherent simplicity and dependability, they are an appealing alternative for long-duration missions such as geostationary satellites, and their compatibility with lengthy operational periods provides constant and steady performance throughout the satellite's service life [57].

A conventional water resistojet thruster conducts liquid vaporization and vapor heating to high temperature in a single cavity integrated with a nozzle. It enables a compact thruster system but suffers from complicated two-phase flow physics and heat loss to the surrounding components [11].

In contrast, AQUARIUS separates the two processes and conducts the vaporization at low temperature. This separation significantly simplifies the physics and increases the reliability of the system. Although the system requires an additional cavity dedicated to vaporization, the cavity will be shared by multiple thrusters and will make the structure of the thruster heads simpler, minimizing the additional resources required [11]. A resistojet is distinguished by its ability to utilize multiple propellants, operate at low thrust, operate over a wide operating range, sacrifice performance for longevity, have a small volume and mass, are easily designed, have simple interfaces, and achieve high specific impulses [57]. In a resistojet, electrical power is transmitted to the propellant via an electric heating element. A heating chamber is used to increase the temperature of the propellant before directing it to the nozzle [58].

While AQUARIUS does have different phases, such as electrolysis and thrust, it cannot be considered a multi-mode propulsion system because it is primarily an electric propulsion system and it does not switch between a high-thrust chemical mode and a low-thrust electric mode, which is a characteristic of a multi-mode propulsion system [59].

In terms of the electric mode of propulsion, the mass of the power processing unit (PPU), shown in Table 3, associated cables, and switches, as well as the powertrain components of the electric thruster itself will have a substantial effect on the overall propulsion system mass [59]. It should be between the power source and the thruster's heating element, regulating power to convert liquid water into gas form.

Table 3. Mass and Volume of CubeSat PPUs [59].

Power (W)	Volume (U)	Mass (g)
9	0.127	83
12	0.127	85
15	0.127	87
27	0.153	129
39	0.153	133
42	0.153	137
72	0.153	139

The AQUARIUS is composed of (see Figure 13):

- 2 Delta-V Thrusters
- 4 Reaction Control Thrusters
- 8 Filters
- Tank Pressure Sensor
- Gas Drain Valve
- Water Drain Valve
- Water Pressure Sensor
- Pressuring Tank
- Water Bladder
- 4 Regulation Valves
- VC Drain Valve
- Vaporization Chamber
- Vaporization Chamber Pressure Sensor
- 4 Delta-V Thruster Valves
- 4 Reaction Thruster Valves

AQUARIUS consists of three key parts: a tank for storing the liquid water, a vaporization chamber for vaporizing the liquid water, and thrusters for generating the thrust (see Fig. 13). The structural specification is on Appendix A [60]. The propulsion system uses a monopropellant system with water as a propellant, and it reduces the structural mass ratio because it is stored in a liquid state under normal temperature and pressure [60]. Liquid fuel can flow for arbitrarily long times and the microthrusters can be refueled. However, the disadvantages of liquid fuels are leakages, high pressure storage, technical complication, and contamination problems [61]. Water has long been attracting everyone as a low-pressure, nontoxic, and easy-to-handle propellant [62]. But it has not become a major propellant because there are higher performance propellants (e.g., hydrazine and xenon). Furthermore, water has the potential advantage in terms of *in-situ* resource utilization in future missions [15]. Meanwhile, for a CubeSat the circumstances are different, where safety and handling ability become as important as performance [63]. In the case of a CubeSat, which is usually launched as a rideshare payload, propellants that offer low pressure storage, easy handling and high energy density are highly desirable [15].

One big downside of using this system is that for propulsion systems with liquid propellants, they tend to experience relatively large changes in mass and center of mass position throughout the mission, meaning that for the success of this mission relies al so on the correct estimation of the mass property and its discharged water mass on orbit [12]. For these, three main methods are used such as the Water Tank Profile, the Temporal Integral of the Vaporization Chamber in each shot, and the Empirical Method from the Water Tank Pressure and Water Temperature.

The remarkable features of this system are the usage of water as propellant and the unification of two types of thrusters by the single propellant [63]. The subsystem is equipped with two 4mN Delta-V thrusters and four 2mN Reaction Control thrusters equipped with flow control valves, their performance specification is on Table 4 (see also Appendix B)[57].

Table 4. Specifications of AQUARIUS[8].

Propellant	Water (<100kPa)
Thrust	• 4mN for Delta-V thruster • 2mN for RCS thruster
Specific Impulse	70 s
Heating	+ 100 K
Power Consumption	< 20 W
Volume (CubeSat Unit)	2.0 U

The selected thruster head(s) is/are activated by opening their respective thruster valve(s), while the other valves are kept closed. A certain amount of water is vaporized at saturated vapor pressure and room temperature [12].

Then the water vapor is heated and accelerated at a thruster head. Inside the tank, 1,224 cm^3 of liquid water is stored in the bladder [60] . The water tank is made of aluminum (A5052) and has an internal bladder (see Fig. 8) that stores approximately 1200 g of water [11] (Appendix C). The CubeSat went under extensive qualification to meet the requirements imposed by in-space environment and launch vehicle specifications, as well as performance tests at ground facilities such as a vacuum chamber [15]. The tank is equipped with two pressure sensors that are used to estimate the injected propellant mass [11]. The pressurized gas, argon [60], kept at 50kPa [11] is stored between the tank and the bladder in a gap space [8]. The argon gas pressure p_{tank} was measured by the tank pressure sensor. The pressure of liquid water stored in the bladder was also measured by the water pressure sensor, which confirmed to be equal to p_{tank}. The temperatures of the tank T_{tank} and the liquid water T_{water} were measured using temperature sensors [15].

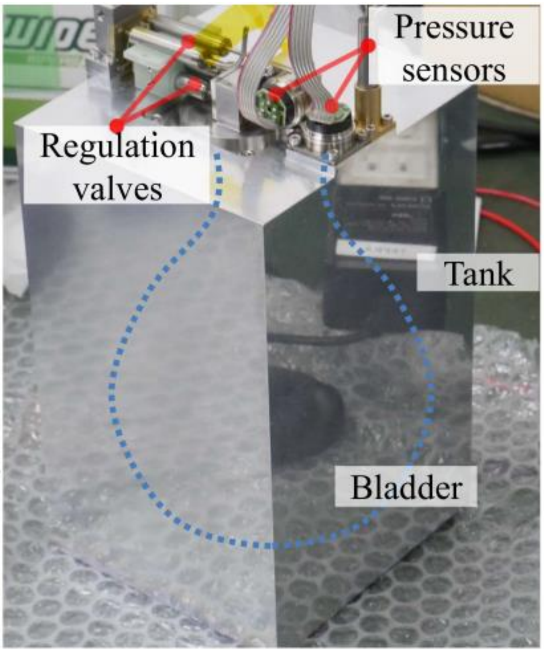


Figure 8. Tank [11].

Following the bladder, four regulation valves are employed; two arranged in series and the other two are parallel [15].

The bladder supplies the water to the vaporization chamber through the opening of a regulation valve, through the blow-down method where two of the four regulation valves in series, positioned downstream of the tank, open for propellant introduction [12].

During a brief opening of the regulation valve, a small number of droplets are injected into the vaporization chamber (see Fig. 9) owing to the pressure difference. Each thruster is connected to the vaporization chamber through a soft tube made of fluororesin [60].

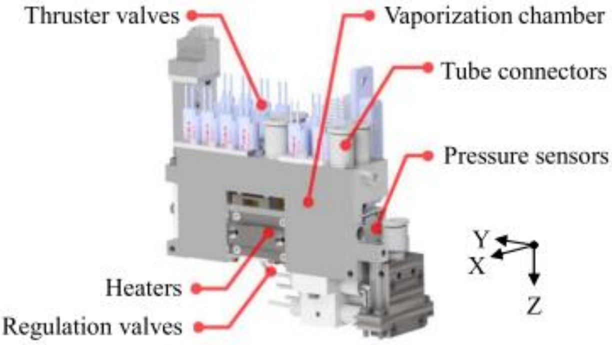


Figure 9. Vaporization Chamber [11].

After water has been supplied, the vaporization chamber is now filled with saturated water vapor.

The vaporization chamber serves the crucial purpose of achieving optimal gas-liquid separation. It consists of two main components: a dedicated space for water droplet vaporization and 3D-printed labyrinthine flow paths. The injected water droplets are effectively captured by the chamber walls due to their surface tension [15]. Two pressure sensors and two temperature sensors are mounted on the chamber to control the heaters and regulation valves [11], from the two pressure sensors it is possible to estimate the presence of water remaining in the chamber [15]. Pressure inside the vaporization chamber is about 2–3 kPa, corresponding to the vapor pressure of water at 20–30 °C [11]. The vaporization chamber temperature, T_{vap}, is maintained at approximately 31°C using 3 electrical heaters [15] and by the waste heat from communication components, shown in Figure 10. Heat is transferred from the wall to the water, raising its temperature and eventually vaporizing it [64]. The communication system emits a high amount of waste heat, on the other hand, the AQUARIUS needs abundant heating in order to vaporize liquid water to generate thrust. Even though liquid water as a propellant is valuable in small satellites, its disadvantage lies in the high latent heat. To address this, a power saving strategy has been implemented by optimizing the configuration design [15]. Because of that, the excess heat of the communication devices can be reused to help the vaporization process. To accomplish this, the vaporization chamber is placed between the transponder slices through thermal conductors [65].

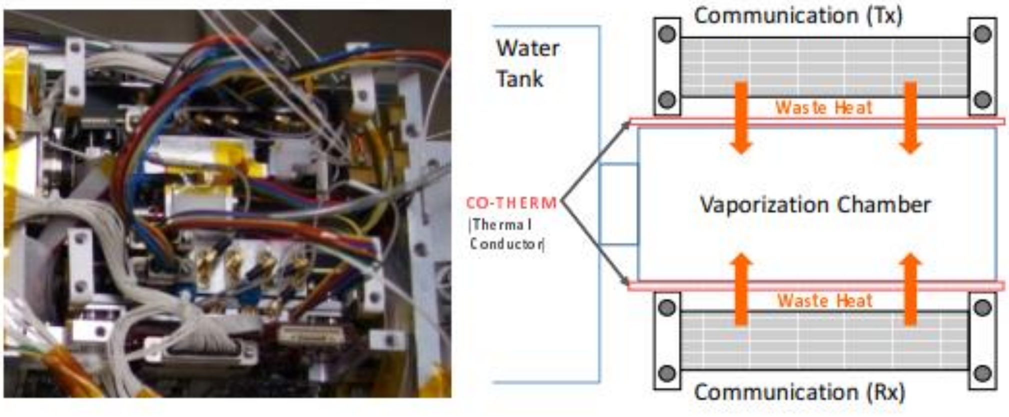


Figure 10. Reuse of waste heat for vaporizing water fuel [65].

The saturated water vapor is supplied to the pre-heater and then heated. The pre-heater, which is made of aluminum, has a helical flow pass in it to increase the heating area, which is heated by heating the outside of aluminum. These helical flow paths are designed to prevent downstream escape of water to the nozzles [15]. At the nozzle, the heated water vapor is accelerated [8]. Vapor flows from the cavity to each nozzle by actuating the corresponding thruster valves. X-band transponder (XTRP) is attached to the vaporization chamber in order to utilize its waste heat and save heater input energy for the propulsion system[11].

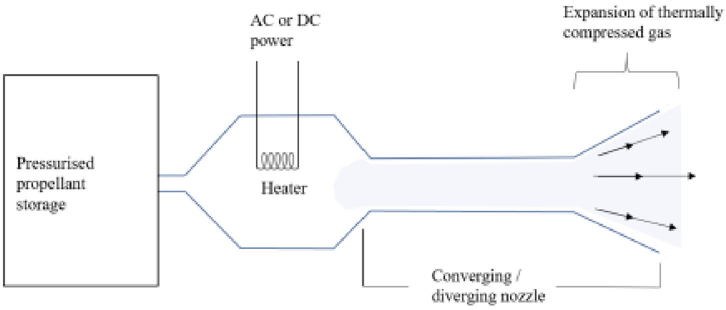


Figure 11. A resistojet thruster as a simplified schematic diagram [66].

Each thruster consists of a thermal insulator, a heater, and a nozzle, shown in Figure 12. The heater is wrapped around the nozzle to warm the in-flowing gas to about 100 °C. The insulator thermally decouples the nozzle from the spacecraft structure so that the heat input from the heater is effectively used to heat up the gas flow [11]. This system appears to not be affected by the nozzle theory, meaning that the specific impulse does not increase with the nozzle temperature, being relatively marginal for this resistojet [15]. The specific impulse, which is the thrust produced by unit of spent fuel mass rate, is also the exhaust gas velocity divided by the acceleration of gravity at ground level. It is a measure of propellant efficiency and is mostly dependent on the technology and its implementation. The temperature of the thruster heads is maintained around 70 °C to prevent water from condensation[12]. The nozzle temperatures must be sufficiently higher than the T_{vap} to prevent condensation of water vapor, but also if they are too high that can lead to difficulty in the material selection near the nozzles, that could compromise the mission [15].

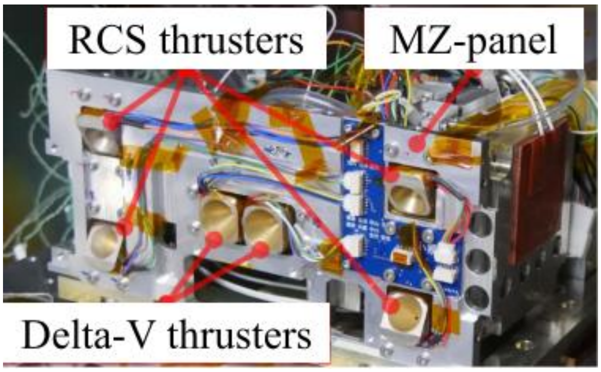


Figure 12. Thruster-heads [11].

The six thruster-heads are divided into two types of thrusters: Delta-V thruster (DVT) and reaction control system thruster (RCT), shown in Figure 11. The nozzle of the RCT has a cant angle for attitude control (angular momentum desaturation) [11]. The attitude of a satellite is when a satellite orientation relative to a reference frame, which can be inertial, can be relative to the Earth or to in this case EQUULEUS uses the Moon as its primary reference. The lifetime is mainly limited by the valves, which have a maximum number of cycles allowed. Especially for small resistojets, contaminants that could obstruct the very small nozzle are a possible life-limiting factor that is neither easily definable nor predictable [6].

AQUARIUS is mainly used for two types of operations, such as delta-V operations and trajectory correction maneuver operations. Each RCT thruster head does not have a pressure sensor, contrary to DVTs. The operation methods between DVTs and RCTs also differ. The nominal discharged water mass per shot is 0.63 g for DVTs and 0.17 g for RCTs. In contrast to DVTs, which use only a single thruster head, two of the RCT thruster heads are used for angular momentum management. The first kind of operations are the ones where the required delta-V for the orbital transfer is generated, while the trajectory correction maneuver operations involve correcting orbital errors through delta-V operations or through controlled flybys [12].

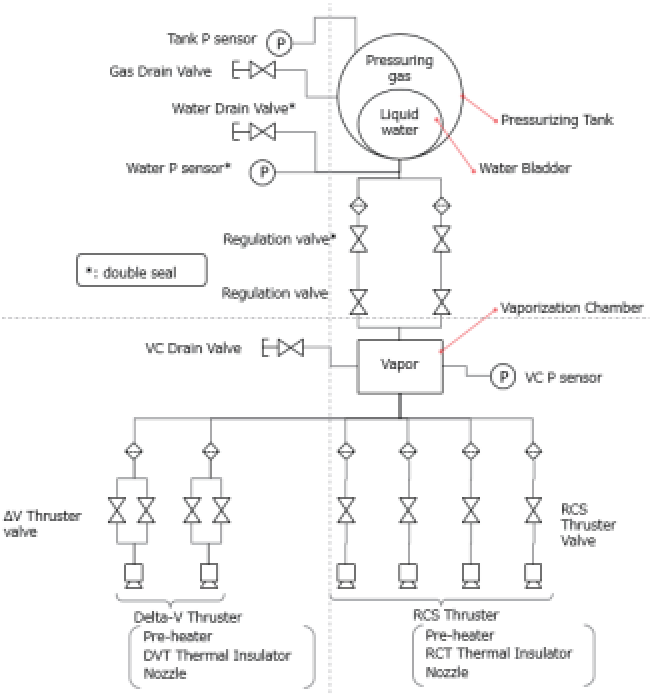


Figure 13. A system diagram of AQUARIUS [8].

The Delta-V Thrusters provide the main propulsion force to adjust the CubeSat's trajectory, enabling orbital maneuvers. These systems are integral to satellite positioning, station-keeping, interplanetary navigation, and spacecraft docking operations. Delta-v thrusters typically rely on monopropellant, bipropellant, or electric propulsion to generate the necessary thrust while minimizing propellant consumption, ensuring prolonged mission duration by maximizing propellant utilization. Facilitates fine-tuned control of a spacecraft's speed and direction to achieve specific orbital transfers or trajectory corrections [5, 17]. The thruster consists of a thermal insulator made of polyamide-imide, a nozzle made of anodized aluminum, a polyamide-imide film heater, and a temperature sensor. Because the polyamide-imide has a low thermal conductivity of 0.29W/K, the exhaust heat from the nozzle to the satellite can be suppressed [60]. It would be ideal if the center of gravity aligned precisely with the thrust vectors of the DVTs, but has shown before, it is impossible to accomplish this because of a misalignment of the nozzles and the gradual shift in the center of gravity arising from propellant consumption [15].

The Reaction Control (RCS) Thrusters are responsible for attitude control. The RCS Thrusters can provide small amounts of thrust in any desired direction and are also capable of providing torque to allow control of rotation, enabling fine orbital adjustments and position corrections without using the main propulsion system, shown in Figure 14. The controlled release of gases also helps manage temperature extremes in propulsion systems by dissipating heat generated during operation [18, 19].

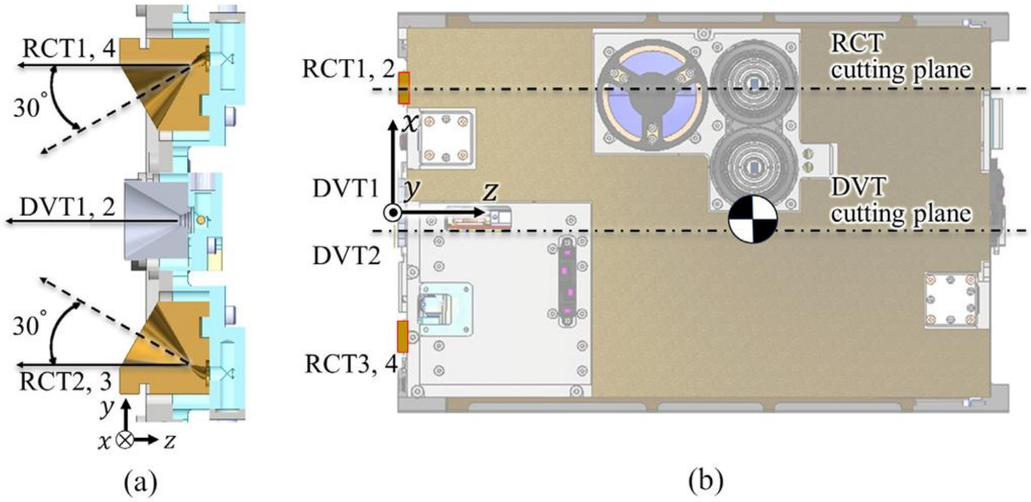


Figure 14. (a) Cross-sectional view in the *yz* plane of the spacecraft, view of a DVT is added to that of RCTs to clarify the direction of each thruster head. While the DVT is oriented in the *z* direction, RCT1,2,3, and 4 are each tilted 30◦ towards the *y* plane through which the thrust axis of DVTs passes. (b) The view of the spacecraft from +*y* direction, the chained lines represent the cutting planes [12].

The Tank Pressure Sensor is essential for the propulsion system. It monitors the internal pressure of the propellant storage tanks, ensuring that the system operates safely and efficiently, preventing over-pressurization that could lead to tank rupture. And helps to regulate propellant release to thrusters for precise thrust control [20, 21].

Water pressure sensor monitors the pressure within water storage and delivery components, ensuring the system operates within safe and efficient parameters, ensuring that the water is delivered to the vaporization chamber at appropriate pressures to achieve desired thrust levels, while continuously measuring the pressure within the water tank and pipelines to detect anomalies such as leaks or blockages [22-25].

The Vaporization Chamber Pressure Sensor is a critical component in systems where vacuum or low-pressure environments need to be monitored, ensuring that vacuum systems operate efficiently and safely. For that it triggers alarms or automatic shutdowns when the vacuum pressure deviates from safe operating limits, protecting equipment from damage and preventing hazardous conditions[17, 26].

Vaporization Chamber is a key component in propulsion systems, composed of aluminum and manufactured using 3D printing to create the vaporizing room and inner labyrinth-shaped flow paths [60], the vaporization chamber separates vapor from liquid droplets and feeds only vapor to the thrusters. The vaporizing room, the volume and surface area of which were designed to be

8.6 cm^3 and 11.2 cm^2, respectively, is explicitly larger than the flow path cross-section of 27 mm^2 to catch droplets using the droplet surface tension [15, 27]. These chambers ensure the propellant is vaporized at the correct pressure and temperature before it enters the engine combustion or expansion section, preventing issues such as incomplete vaporization or propellant degradation and regulate the flow of propellant into the vaporization chamber to prevent issues such as vapor lock or inadequate fuel delivery [15, 28]. The vaporization chamber is cooled by the evaporation of water droplets. Therefore, if a hot device is thermally connected to the vaporizing chamber, the heat can be used to warm the vaporizing chamber. Helping to compensate for the vaporization heater power, which in this case is the communication device, the device that consumes the largest amount of power.

Outside the vaporization chamber, ceramic heaters are mounted to keep the temperature constant [60].

A water bladder is a flexible, durable container designed to store water. These bladders are often made from materials such as rubber, PVC, or TPU, which can withstand pressure, temperature fluctuations, and environmental stresses, allowing them to expand as they fill with water and contract as the water is used. While durable, water bladders can be more susceptible to punctures or tears than rigid containers, requiring careful handling [78].

The drain valve in the Vaporization chamber plays a crucial role in managing and controlling fluid flow during system operation. It ensures the chamber is properly drained when necessary, preventing fluid build-up that could impact performance or safety [60]. The valve operates automatically or manually to regulate the release of excess water or vaporized gases from the chamber, while helping to regulate the temperature of the chamber by discharging hot fluids or vapor when necessary, preventing overheating or thermal imbalance maintaining the chamber's functionality and efficiency [79].

A gas drain valve plays a critical role in safely removing excess gas or venting trapped gases from a system, ensuring optimal operational conditions [80]. These valves are crucial for maintaining system stability and preventing pressure build-up that could compromise performance or safety. In systems where gas may carry moisture or impurities, drain valves help expel these unwanted elements, maintaining system cleanliness and functionality. Monitoring valve activity can indicate unexpected gas accumulations, which may indicate leaks or malfunctions in the system [30, 32].

A water drain valve is essential for efficiently removing accumulated water from systems, ensuring smooth operation, and preventing issues related to fluid retention. Ensuring that excess or not vaporized water does not accumulate in the vaporization chamber or delivery lines. During maintenance or shutdown, the valves allow for complete system purging to prevent contamination and prepare the propulsion system for subsequent operation cycles [5, 22].

A regulation valve plays a vital role in controlling the flow rate, pressure, or direction of gases or liquids within a system, ensuring optimal operating conditions. It manages the precise delivery of water or gas propellant to the vaporization chambers, directly influencing thrust levels and propulsion efficiency. The automated regulation valves contribute to system safety by dynamically adjusting flow in response to changing operational demands or system anomalies [82]. For redundancy, these valves are serially and parallelly connected [60].

Filters are critical components in maintaining the cleanliness and efficiency of propulsion systems. They remove contaminants such as particles, debris, and moisture from fluids, which can damage system components to help maintain dry conditions to prevent corrosion and chemical reactions, ensuring that systems operate under optimal and safe conditions [83]. By preventing contaminants from entering sensitive components like valves, pumps, and vaporization chambers, filters extend equipment life, reduce maintenance requirements, and help stabilize system pressure by maintaining consistent flow conditions, preventing sudden pressure drops or spikes caused by clogging [84].

A pressurizing tank is an essential component in propulsion systems. It maintains stable system pressure by storing and supplying pressurized gas or fluid to drive operational processes. Support stable thrust generation by maintaining the required pressure for delivering propellants to vaporization chambers or combustion. These tanks ensure that pressure levels remain within optimal ranges, supporting system performance, efficiency, and safety [5, 36, 37]. A Delta-V thruster valve is integral to the control and operation of spacecraft propulsion systems, specifically for performing precise maneuvers that adjust the spacecraft trajectory or orbital velocity. These valves regulate the flow of propellant to the thrusters, ensuring efficient and accurate thrust generation. Facilitate smooth startup and shutdown of thruster operations, optimizing fuel usage and minimizing wear. Two valves are used in parallel for each Delta-V thruster, as shown in Figure 13, to maximize the flow conductance in a limited volume. While the probability of failure increases due to parallel arrangement, higher thrust is needed to achieve the mission [15, 38].

A Reaction Control Thruster valve is a key component in spacecraft propulsion systems used for attitude control, orbit adjustment, and fine-tuned maneuvering. These valves regulate the flow of pressurized propellant to small thrusters mounted on the spacecraft, ensuring precise directional changes and stability. Incorporate features such as pressure relief or shut-off capabilities to prevent over-pressurization or unintended thruster firing. For the Reaction Control Thruster, each thruster has a single thruster valve because the Reaction Control Thruster does not require a large amount of thrust [15, 19, 38].

Initial checkouts of AQUARIUS were completed within several time frames of 6.5 hours in total (Appendix D), during the checkout phase, all valves and heaters were checked to see if they were functioning properly, and the torque and thrust were analyzed to see if they were sufficient to meet the mission requirements [15].

After the initial checkout, EQUULEUS executed its first orbital maneuver, the delta-V operation, the DV1 operation, which aimed to raise the perilune altitude. As a result of the DV1 operation, the satellite effectively remained in the Earth-Moon system after the subsequent lunar fly by. After the DV1 operation, the first trajectory control maneuver, the TCM1 operation, was performed to further fine-tune the satellite's trajectory [15]. The satellite experienced different equilibrium temperatures, with relatively high temperature sob served during the DV1 operation and lower temperatures during the TCM1 operation.

3.2 Severity Categories

To ensure methodological consistency and relevance within the aerospace context, the failure analysis conducted for the Aquarius propulsion system follows the ECSS standard [88]. This norm was specifically developed to address the unique environmental and operational challenges encountered in space missions, such as vacuum exposure, radiation, thermal extremes, and the inability to service systems post-launch.

Unlike conventional industrial FMEA approaches, ECSS-Q-ST-30-02C [88], which are often tailored to automotive/manufacturing sectors, the ECSS methodology offers a domain-specific framework that is crucial for capturing the criticality and cascading nature of failures in space systems.

The structured nature of the standard facilitates comprehensive risk identification and prioritization while enabling seamless integration with broader ECSS-based reliability and risk management strategies, its use fosters international credibility and compliance [88]

A severity level is assigned to each assumed failure mode according to its effect. The Severity Levels are in accordance with the Table 5 [88].

Table 5. Severity Categories [88].

Severity	Name	Categories
1	Catastrophic	Risk of propagation to upper level
2	Critical	Assumed failure mode results in complete loss of mission or functionality
3	Major	Assumed failure mode results in major degradation of mission or functionality
4	Negligible	Assumed failure mode results in negligible degradation of mission or functionality

3.3 Critical Single Point Failure (SPF) List

AQUARIUS has mostly a mechanical/structural origin, and their probability of occurrence is minimized by incorporating safety factors. A Single Point Failure (SPF) is part of a product that, if it fails, will result in the unrecoverable failure of that product; this is the definition provided by ECSS-S-ST-00-01C Rev. 1 [28]. Usually SPFs, in standard space projects, need to be approved by the customer.

Critical Single Point Failure are listed in the Table 6 for the AQUARIUS.

Table 6. Critical Single Point Failure.

SUBSYSTEM	EQUIPMENT/ITEM	QTY	FAILURE MODE	SYSTEM EFFECT (Main)	SEV. LEVEL	REMARKS
Propulsion Tanks	H_20 Tank	1	Burst Rupture/Leak during Launch	Loss of tank. Damage/loss of Satellite/Launcher.	1	Tank subject to safe life design/fracture design
Propulsion Engines	Delta-V THR	2	External leakage Burst	End or curtailment of the mission or impossibility to achieve requirements	2	
	RCS THR	4	External leakage Burst	End or curtailment of the mission or impossibility to achieve requirements	2	
Propulsion Piping & Probe	Filters	8	External leakage/clogging	End or curtailment of the mission or impossibility to achieve requirements	2	
	Drain Valves	3	External leakage	End or curtailment of the mission or impossibility to achieve requirements	2	
	Regulation Valves	12	External leakage	End or curtailment of the mission or impossibility to achieve requirements	2	
	Pressure Sensors	3	Burst Loss of signal	End or curtailment of the mission or impossibility to achieve requirements	2	
	Vaporization Chamber	1	Loss of signal	End or curtailment of the mission or impossibility to achieve requirements	2	

Description of the table:

- Column 1 – identifies the analyzed subsystem.
- Column 2 - identifies the analyzed equipment or item.
- Column 3 – quantity of the element.
- Column 4 - identifies the failure mode of the element.
- Column 5 – presents the effect of this failure.
- Column 6 - presents the associated severity at satellite level.
- Column 7 – remarks.

3.4 FMEA

In Table 7, it is shown an FMEA conducted on AQUARIUS. This FMEA table identifies each item, its function and then identifies potential failure modes, and its effects on the equipment, on the subsystem and on the satellite. Through that a severity number is associated according to the failure in question [88].

Table 7. FMEA

Nº	ITEM/BLOCK	FUNCTION	ASSUMED FAILURE MODE	EFFECTS ON: A-EQUIPMENT B-SUBSYSTEM C-SATELLITE	OBSERVABLE SYMPTOMS	PREVENTIVE// COMPENSATORY PROVISIONS	SEV.	PARAMETER MONITORING
1	Tank or tubing	Propellant & piping	Burst	A, B: Damage to other parts of satellite due to fragments; high risk of destruction of some vital element. Destruction of surrounding equipment by propellant leakage C: No possibility to reach orbit or restriction of the mission	No signal or variation of signal	None	1	NA
2	Tank or tubing	Propellant & piping	External leakage	A, B: No or degraded trust. Destruction of surrounding equipment by propellant leakage C: No possibility to reach orbit or restriction of the mission	No signal or variation of signal	None	2	NA

3	Tank or tubing	Propellant & piping	Clogging	A, B: No or degraded trust C: No possibility to reach orbit or restriction of the mission	No signal or variation of signal	None	2	NA
4	Tank or tubing	Propellant & piping	Leakage or rupture	A: Incorrect spacecraft positioning during thrusters firing B: incorrect satellite control C: Degradation of the mission	No signal or variation of signal	None	2	NA
5	Vaporization Chamber	Propellant & piping	Telemetry	A, B: Loss of attitude control or satellite position C: No possibility to reach/keep in orbit, restriction of the mission	No signal or variation of signal	None	2	NA
6	Gas Drain Valve	Valve	External leakage	A, B: No or wrong pressure regulation of propellant tanks. No or degraded thrust C: Restriction of the mission	No signal or variation of signal	None	2	NA
7	VC Drain Valve	Valve	External leakage	A, B: No or wrong pressure regulation of vaporization chamber. No or degraded thrust C: Restriction of the mission	No signal or variation of signal	None	2	NA
8	Water Drain Valve	Valve	External leakage	A, B: No or degraded thrust. Destruction of surrounding equipment by propellant leakage C: Restriction of the mission	No signal or variation of signal	None	2	NA
9	Water Drain Valve	Valve	Internal leakage	A, B: Loss of redundancy protection C: No effect if no other failure occurs	No signal or variation of signal	None	2	NA
10	Regulation Valve	Valve	External leakage	A, B: No or degraded thrust C: Loss of mission or restriction of the mission	No signal or variation of signal	Redundant	2	NA
11	Regulation Valve	Valve	No opening of the valve	A, B: No thrust C: Loss of mission or restriction of the mission	No signal or variation of signal	Redundant	2	NA
12	Regulation Valve	Valve	- Inopportune	A, B: Premature loss of propellant isolation	No signal or variation of signal	Redundant	4	NA

			opening of the valve -Internal leakage	C: No or minor effect on the mission				
13	RCS Thruster Valve	Valve	External leakage	A, B: No or degraded thrust C: Loss of mission or restriction of the mission	No signal or variation of signal	None	2	NA
14	RCS Thruster Valve	Valve	No opening of the valve	A, B: No thrust C: Loss of mission or restriction of the mission	No signal or variation of signal	None	2	NA
15	RCS Thruster Valve	Valve	-Inopportune opening of the valve -Internal leakage	A, B: Premature loss of propellant isolation C: No or minor effect on the mission	No signal or variation of signal	None	2	NA
16	Filter	Filtering	External leakage	A, B: No or degraded thrust C: Lost mission or restriction of the mission	No signal or variation of signal	None	2	NA
17	Filter	Filtering	Clogging	A, B: No or degraded thrust C: Loss mission or restriction of mission	No signal or variation of signal	None	2	NA
18	Thruster	Actuator	Ono mono-stable valve stays partially open	A, B: Loss of thrust, loss of water C: Restriction of the mission	No signal or variation of signal	None	2	NA
19	Thruster	Actuator	One mono-stable valve stays closed	A, B: No thrust C: Restriction of the mission	No signal or variation of signal	None	2	NA
20	Thruster	Actuator	Loss or degradation of thermal heating of thruster	A, B: Loss of thruster C: Restriction of the mission	No signal or variation of signal	None	2	NA
21	Thruster	Actuator	Internal leakage	A, B: Loss of thruster, loss of water C: Restriction of the mission	No signal or variation of signal	None	2	NA
22	Thruster	Actuator	External leakage after thruster valve (second seat)	A, B: Unwanted degraded thrust. Loss of attitude control or satellite position C: No possibility to reach/keep in orbit, restriction of the mission	No signal or variation of signal	None	2	NA
23	Thruster	Actuator	External leakage before thruster	A, B: Unwanted degraded thrust. Loss of attitude	No signal or variation of signal	None	2	NA

			valve (first seat)	control or satellite position C: No possibility to reach/keep in orbit, restriction of the mission				
24	Water Sensor	Sensor	Telemetry	A: Loss of the sensor signal B: Loss of attitude control or satellite position C: No possibility to reach/keep in orbit, restriction of the mission	No signal or variation of signal	None	2	NA
25	Tank Sensor	Sensor	Telemetry	A: Loss of the sensor signal B: Loss of attitude control or satellite position C: No possibility to reach/keep in orbit, restriction of the mission	No signal or variation of signal	None	2	NA
26	VC Sensor	Sensor	Telemetry	A: Loss of the sensor signal B: Loss of attitude control or satellite position C: No possibility to reach/keep in orbit, restriction of the mission	No signal or variation of signal	None	2	NA

3.5 FMEA Analysis

For The FMEA analysis, was followed the order shown on Table 7.

- Column 1 – number of the item.
- Column 2 - identifies the analyzed equipment or item.
- Column 3 – identifies its function.
- Column 4 - identifies the assumed failure mode of the element.
- Column 5 – presents the effect of the failure on: A-Equipment, B- Subsystem, C-Satellite.
- Column 6 - presents the observable symptoms.
- Column 7 – presents preventive/compensatory provisions.
- Column 8 - presents the associated severity at satellite level.

- Column 9 – remarks.

The system analysis is divided by functions: Propellant and piping, Valve, Filtering, Actuator and Sensor.

Within the propellant and piping function, the items that were taken into consideration were the tank or tubing and the vaporization chamber. Starting with the tank or tubing, there were four assumed failure modes: Burst, External leakage, Clogging and Leakage or Rupture.

In case of burst, the implications for the equipment and the subsystem are the same, it damages other parts of the satellite, due to fragments, high risk of destruction of some important element, destruction of the surrounding equipment by the leakage of propellant. The implications on the satellite are very serious, meaning no possibility to reach orbit or restriction of the mission. The observations seen are the variation of the signal/ no signal. Which attributes the level 1 severity, meaning that, according to Table 5, it is catastrophic, the risk of propagation to upper level.

In case of external leakage, the implications for the equipment and the subsystem are the same, it occurs no or degraded thrust, and the destruction of the surrounding equipment by the propellant leakage. The implications for the satellite are the same as the previous one, no possibility of reaching orbit or restriction of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

In case of clogging, the implications on the equipment and the subsystem are the same, it occurs no or degraded thrust. The implications for the satellite are the same as the previous one, no possibility of reaching orbit or restriction of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

In case of leakage or rupture, the implication on the equipment is the incorrect spacecraft positioning during the thrusters firing. The implication for the subsystem is the incorrect satellite control. The implication for the satellite is degradation of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 of severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

For the vaporization chamber, there was only an assumed failure mode which is the telemetry. Telemetry is periodic information transmitted by the satellite, further to payload data. It contains mandatory information such as battery voltage and/or change, critical temperatures, attitude, COMMs system health, OBC uptime/memory usage/reboots, position and orbit, time information, radio beacon signal. The list of telemetries related to this system are on Appendix E. In that case, the implications on the equipment and the subsystem are the same, it occurs loss of attitude control or satellite position. The implication for the satellite is the no possibility to reach/keep in orbit and the restriction of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

Now, for the valve function, there are six valves that were analyzed: Gas Drain Valve, VC Drain Valve, Water Drain Valve, Regulation Valve and RCS Thruster Valve.

Beginning with the gas drain valve, in the case of external leakage, the implications for the equipment and the subsystem are the same, there is no or wrong pressure regulation of the propellant tanks. The implication for the satellite is the restriction of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

For the VC drain valve, in the case of external leakage, the implications for the equipment and the subsystem are the same, there is no or wrong pressure regulation of the vaporization chamber, no or degraded thrust. The implication for the satellite is the restriction of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

For the water drain valve, in the case of external leakage, the implications for the equipment and the subsystem are the same, there is no or degraded thrust, destruction of the surrounding equipment by the propellant leakage. The implication for the satellite is the restriction of the mission. In case of Internal leakage, the implications on the equipment and the subsystem are the same, the loss of redundancy protection. The implication for the satellite is that there is no effect if no other failure occurs. The observations seen in both are the variation of the signal/ no signal. Both have been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

For the regulation valve, in the case of external leakage, the implications for the equipment and the subsystem are the same, there is no or degraded thrust. The implication for the satellite is the restriction of the mission or the loss of the mission. The observations seen are the variation of the signal/ no signal. The preventive action is that the valve is redundant. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

In the case of no opening of the valve, the implications for the equipment and the subsystem are the same, there is no thrust. The implication for the satellite is the restriction of the mission or the loss of the mission. The observations seen are the variation of the signal/ no signal. The preventive action is that the valve is redundant. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

In the case of inopportune opening of the valve or internal leakage, the implications for the equipment and the subsystem are the same, there is premature loss of the propellant isolation. The implication for the satellite is no or minor effect on the mission. The observations seen are the variation of the signal/ no signal. The preventive action is that the valve is redundant. Which has been attributed the level 4 severity, according to Table 5, meaning negligible, assumed failure mode results in negligible degradation of mission or functionality.

For the RCS thruster, in the case of external leakage, the implications for the equipment and the subsystem are the same, there is no or degraded thrust. The implication for the satellite is the restriction of the mission or the loss of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

In the case of no opening of the valve, the implications for the equipment and the subsystem are the same, there is no thrust. The implication for the satellite is the restriction of the mission or the loss of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

In the case of inopportune opening of the valve or internal leakage, the implications for the equipment and the subsystem are the same, there is premature loss of the propellant isolation. The implication for the satellite is no or minor effect on the mission. The observations seen are the variation of the signal/ no signal. The preventive action is that the valve is redundant. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

For the filtering function, the analyzed components were the filters. In case of external leakage and in case of clogging, the implications for the equipment and the subsystem are the same, there is no or degraded thrust. The implication for the satellite is the restriction of the mission or the loss of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

For the actuator function, the analyzed components were the thrusters. In the case of one mono-stable valve staying partially open, the implications for the equipment and the subsystem are the same, there is loss of thrust and loss of water. The implication for the satellite is the restriction of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

In the case of one mono-stable valve staying closed, the implications for the equipment and the subsystem are the same, there is loss of thrust. The implication for the satellite is the restriction of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

In the case of loss or degradation of thermal heating of thruster, the implications for the equipment and the subsystem are the same, there is loss of thrust. The implication for the satellite is the restriction of the mission. The observations seen are the variation of the signal/ no signal.

Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

In the case of internal leakage, the implications for the equipment and the subsystem are the same, there is loss of thrust and loss of water. The implication for the satellite is the restriction of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

In the case of external leakage after thruster valve (second seat), the implications for the equipment and the subsystem are the same, there is unwanted degraded thrust, loss of attitude control or satellite position. The implication for the satellite is the inability to reach/keep in orbit, restriction of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

In the case of external leakage before thruster valve (first seat), the implications for the equipment and the subsystem are the same, there is unwanted degraded thrust, loss of attitude control or satellite position. The implication for the satellite is the inability to reach/keep in orbit, restriction of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

For the sensor function, the analyzed components were the water sensor, the tank sensor, and the VC sensor. In the case of telemetry, the implications for the equipment are the loss of the sensor signal. The implications for the subsystem are the loss of attitude control or satellite position. The implication for the satellite is the inability to reach/keep in orbit, restriction of the mission. The observations seen are the variation of the signal/ no signal. Which has been attributed the level 2 severity, according to Table 5, meaning critical, assumed failure mode results in complete loss of mission or functionality.

To conclude this analysis, there are some changes that would be relevant. In Propellant and Piping System, replacing the tank material with burst-resistant materials, such as titanium alloys or composite materials with high tensile strength. The addition of pressure relief valves on the tank to prevent rupture, include also isolation valves near the critical points to help isolate leaks quickly.

Another area would be the valve design, making all of the critical valves fully redundant, design valves with fail-safe options, meaning that in the event of power loss, control signal loss, or system failure, the valve automatically moves to a safe position, usually closed, to prevent hazardous situations such as leaks or loss of propellant. While on leakages, the usage of better sealing materials can help to reduce internal and external leakage. The usage of valves with position sensors and feedback helps to monitor in real-time.

In the Filtering Function, the usage of multi-stage filters can reduce the clogging risk, and the incorporation of pressure drop sensors to signal clogging early.

On Thrusters, the implementation of redundant thermal heaters with automatic switching in case of failure, the usage of high-reliability valves and actuators with extended cycle life, design thrusters with built-in diagnostics to detect valve sticking or leakage; and the addition of feedback sensors on thruster output to detect degraded thrust.

In Sensors and Telemetry, the addition of redundant sensors for critical parameters (tank pressure, temperature, valve position), the usage sensors with self-diagnosis capabilities to detect degradation or faults, the implementation of dual redundant telemetry communication paths with error correction, and the usage diverse sensor technologies to cross-validate data and detect anomalies.

Chapter 4 – Conclusion

This thesis presented a comprehensive analysis of the AQUARIUS micropropulsion system through the application of FMEA. A contextual overview of the EQUULEUS mission—where AQUARIUS was successfully deployed—was provided to support the evaluation of the propulsion system's design, operational principles, and the specific challenges associated with using water as a propellant.

A historical and methodological literature review was conducted to establish a solid foundation in risk assessment practices, particularly in the aerospace sector. The importance of FMEA as a preventive engineering tool was emphasized, followed by a detailed explanation of the methodology, including risk factors, the construction of a risk matrix, and adaptation of severity categories in accordance with the ECSS standard.

The FMEA itself was developed in a structured manner, beginning with a functional breakdown of the AQUARIUS system, followed by the identification and classification of potential failure modes. Special attention was given to the unique constraints of micropropulsion and the limited precedent in using water-based propellants in space applications. Notably, the adaptation of standard FMEA parameters was required, given that many aerospace-specific conventions diverge from those found in more general engineering disciplines—particularly in how severity is quantified and interpreted.

Despite initial skepticism regarding the feasibility of water propulsion, AQUARIUS demonstrated on 16 November 2022 that innovative, sustainable alternatives can meet mission-critical performance requirements. This successful demonstration marks a significant milestone in the evolution of space propulsion, particularly for small-scale and resource-limited platforms such as CubeSats.

The limitations encountered during this research, especially the absence of publicly available aerospace-specific data, underscore the challenges of applying structured risk methodologies like FMEA in emerging technological domains. Nevertheless, this thesis shows that with careful adaptation and contextual awareness, FMEA can provide meaningful insights into the reliability and risk posture of innovative aerospace systems.

In summary, this work contributes both a technical evaluation of AQUARIUS and a methodological framework for applying risk analysis to novel propulsion technologies. It highlights the importance of innovation in the face of uncertainty and the role of rigorous engineering analysis in enabling the future of sustainable space exploration.

4.1 Future Works

While this work provides a foundational risk analysis of the AQUARIUS micropropulsion system, several opportunities for further research and development have been identified throughout the study. These areas could significantly enhance both the performance and reliability of water-based propulsion systems, particularly for small satellite platforms.

One key avenue for future work lies in the optimization of the materials used in the construction of the propellant tanks. Current designs often rely on traditional polymers such as PVC or TPU, which, while effective, may not offer optimal trade-offs between mass, thermal stability, chemical resistance, and structural integrity under varying space conditions. Investigating advanced materials or composite solutions—such as carbon-reinforced polymers or metallic liners—could improve tank performance and reduce risks associated with deformation, leakage, or rupture during thermal cycling and vacuum exposure. These changes could be evaluated through additional failure mode assessments and long-term environmental testing.

Another critical enhancement involves the integration of redundancy within the propulsion system. The current AQUARIUS architecture relies on a single-threaded approach, which increases the vulnerability to single-point failures, especially in mission-critical scenarios. Introducing redundant components (e.g., secondary valves, backup sensors, or parallel propellant lines) could drastically minimize the impact of individual component failures. Such redundancy would also improve fault tolerance, enhance system robustness, and align the design more closely with ECSS reliability standards. Future FMEA iterations should include redundancy modeling to assess how different levels of fault isolation and recovery affect overall mission risk.

While this work is primarily theoretical and qualitative in its risk assessment approach, future research could focus on experimental validation of AQUARIUS components under simulated space conditions. These studies would provide empirical data to refine failure probabilities, improve severity estimates, and validate the effectiveness of proposed mitigation strategies—particularly material upgrades and redundancy mechanisms.

Lastly, an important direction for future development is the adaptation of the AQUARIUS system to multi-mission applications or variable orbital regimes. Extending its capabilities to operate beyond the cis-lunar environment or modifying it for planetary orbiters would require a reevaluation of system requirements, propellant efficiency, and environmental hazards. The scalability and adaptability of the propulsion system could open pathways for broader use across diverse mission profiles.

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Appendix A – Structural Specifications of AQUARIUS.

Table 8. Structural specifications of the AQUARIUS flight model [11].

Parameters	Values
Vaporization room area	11.2 cm^2
Vaporization room volume	8.60 cm^3
Nozzle throat diameter	2.60 mm (DVT) 1.20 mm (RCT)
Nozzle exit diameter	17.9 mm (DVT) 14.6 mm (RCT)
Nozzle axis angle	0° (DVT) 30° (RCT)
Nozzle convergent angle	30°
Nozzle divergent angle	30°
Nozzle cant angle	- (DVT) 30° (RCT)
Thruster valve conductance	1.14×10^{-8} kg/sPa (DTV) 2.86×10^{-9} kg/sPa (RCT)

Appendix B – Thrusters Specifications.

Table 9. Designed Performance of Delta-V and Reaction Control Thrusters operations [60].

Performances	
Delta-V Thruster (DVT)	
Duty cycle	0.35
Average mass flow rate	6.57 mg
Average thrust	4.45 mN
Specific impulse	75.1 s
Reaction Control Thruster (RCT)	
Duty cycle	0.37
Average mass flow rate	1.64 mg
Average horizontal thrust	1.05 mN
Average vertical thrust	0.61 mN
Specific impulse	77.0 s

Appendix C – Weight Distribution.

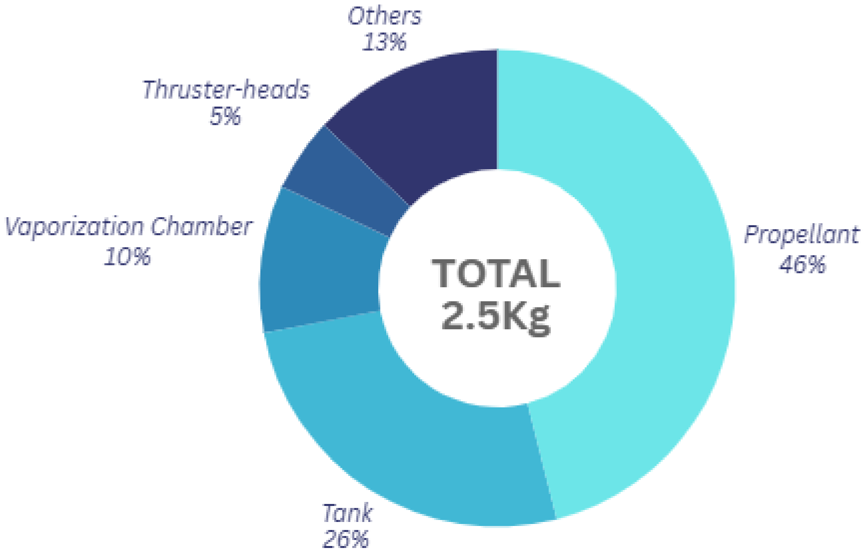

Figure 15. Weight Distribution of AQUARIUS components [89].

Appendix D – Sequence of the initial checkout.

Table 10. Sequence of the initial checkout, the DV1 and TCM1 operations [15].

Time (UCT), date	Event
06:47, 16, Nov.	Launch of the SLS
10:28, 16, Nov.	Separation from the SLS
10:32, 16, Nov.	First telemetry acquired
21:26, 16, Nov.	AQUARIUS checkout start
21:41, 16, Nov.	Thruster valves checkout
22:01, 16, Nov.	Heaters checkout
22:40, 16, Nov.	Regulation valves checkout
23:33, 16, Nov.	RCS's torque measurement
00:53, 17, Nov.	DVT's thrust vector measurement
03:50, 17, Nov.	AQUARIUS checkout end
23:14, 18, Nov.	DV1 operation start
02:35, 19, Nov.	DV1 operation end
01:45, 20, Nov.	TCM1 operation start
02:10, 20, Nov.	TCM1 operation end
16:25, 21, Nov.	The first lunar closest approach

Appendix E – List of telemetries.

Table 11. List of telemetries relating to AQUARIUS acquired in the initial operation of EQUULEUS [15].

Parameter	Nomenclature
Tank pressure	p_{tank}
Tank temperature	T_{tank}
Water pressure	N/A
Water temperature	T_{water}
Vaporization chamber pressure 1	p_{vap}
Vaporization chamber pressure 2	N/A
Vaporization chamber temperature 1	T_{vap}
Vaporization chamber temperature 2	N/A
DVT1 nozzle inlet pressure	p_{DVT1}
DVT2 nozzle inlet pressure	p_{DVT2}
DVT1 nozzle inlet temperature	T_{DVT1}
DVT2 nozzle inlet temperature	T_{DVT2}
RCT1 nozzle inlet temperature	N/A
RCT2 nozzle inlet temperature	N/A
RCT3 nozzle inlet temperature	N/A
RCT4 nozzle inlet temperature	N/A
DVT1 tube* temperature	N/A
DVT2 tube* temperature	N/A
RCT1 tube* temperature	N/A
RCT2 tube* temperature	N/A
RCT3 tube* temperature	N/A
RCT4 tube* temperature	N/A
Communication device temperature	T_{comm}

*Vapor feed lines between the thruster valves and thruster heads.