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ICE : Ice Collection on Enceladus

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Abstract

Of the numerous factors driving our curiosity for the exploration of our Solar System, the possibility of discovering life is perhaps one of the most exciting one. With the end of the *Cassini-Huygens* mission and the findings it uncovered, a new wave of curiosity towards Saturn and its system emerged. Evidence suggests that Enceladus, one of Saturn's moons, has a subsurface ocean that vents out plumes of oceanic material. This allows the investigation of the astrobiological potential of Enceladus without drilling through multiple kilometers of ice crust to get to the subsurface warm ocean. The Ice Collection on Enceladus (ICE) Mission's goal is to investigate the habitability of Enceladus through sample collection from orbit which would then return to Earth while a lander will land on Enceladus' icy surface to execute in situ research.
Keywords: Enceladus, Life research, Mission concept, Spacecraft design, Systems engineering.

Acronyms/Abbreviations

- SLS : Space Launch System
- UV : Ultra-violet
- SOI : Saturn Orbit Insertion
- EnOI : Enceladus Orbit Insertion
- EOI : Earth Orbit Insertion
- CBE : Current Best Estimate
- MEV : Maximum Expected Value
- AOCS : Attitude and Orbit Control Sytem
- ST : Star-Tracker
- IMU : Inertial Measurement Unit
- EOM : End of Mission
- MLI : Multilayer Insulation
- RTG : Radioisotope Thermoelectric Generator
- HGA : High-Gain Antenna

1. Introduction

Evidence suggests that the warm subsurface ocean below Enceladus' icy crust vents out plumes of water vapor and ice from its South Pole. The study of these plumes not only allows to study the habitability of its ocean without digging through the crust, but also allows to test the hypothesis that evidence of life is present at detectable levels of the plumes.

This paper proposes a mission concept taking advantage of the plumes to search for signs of life. The mission consists of an orbiter and a lander with the orbiter collecting samples from orbit as well as scouting for suitable launch sites. Once the sample collection from orbit and the landing scouting is done, the two systems will separate with the lander heading for Enceladus' surface while the orbiter will make its way back to Earth. Once on Enceladus' surface, the lander will execute in situ research looking for signs of life as well as investigating the geochemical and geophysical condition of Saturn's icy moon.

2. Science objectives

2.1 Is Enceladus inhabited ?

1. *Characterize bulk organic function of plume* : define the complexity of organic molecules by measuring the number of chemical steps needed to generate each molecule (Marhsall et al. 2017 [1]).

2. *Search for a polyelectrolyte* : reliance on a polyelectrolyte as a means to store and pass on genetic information could be a universal feature of life (Benner 2017 [2])

3. *Search for any cell-like morphologies* : morphologies ressembling cells can serve as a strong biosignature when collocated with chemical activity like autofluorescence (Bhartia et al. 2010 [3]).

2.2 Is Enceladus habitable ?

1. *Physical and chemical environment* : quantifying the pH, the salinity, and the nutrient and energy sources to define how much biosignal one might except from the subsurface ocean.

2. *Internal structure* : geochemical factors are closely associated with the structure and dynamics of the interior and crust

3. Mission concept overview

- *Round trip trajectory* : Jupiter flyby, Saturn pump-down orbit, Enceladus orbit, Saturn orbit, Earth orbit insertion(see Figure 1 for the full mission timeline)

- *Mission duration* : 27 years

- *Launch window* : October 2038, backup in November 2039
- *Launch site* : Kennedy Space Center (KSC), Florida, USA
- *Launch vehicle* : Space Launch System (SLS) Block 2, payload capacity of 46,000 kg
- *Delta-v budget* : 4,600 m
- *Mass budget* : Total wet mass of 11,030 kg, dry mass with margin of 3,534 kg, science instruments payload of 103 kg
- *Communication* : Ka-band downlink provides a total of 1.2 Tbs of data for the whole mission

October 2038	October 2040	September 2045	March 2050	March 2052
Launch	Jupiter Fly-by + Direct cruise	Saturn orbit insertion + Moon tour	Enceladus orbit insertion + Orbit	Sample return + Enceladus landing

March 2053	October 2056	November 2065	December 2065
End of in situ research	Saturn orbit insertion + Moon tour + Direct cruise	Earth orbit insertion	Earth reentry + Landing

Fig. 1. Mission phases from Launch to End of Life

3.1 *Science phase timeline*

In Figure 2 is the full timeline for the science phase of the mission concept.

March 2050	March 2052		March 2053	December 2065
Enceladus orbit sample collection + landing terrain scouting	Orbiter and Lander separation	Sample return + Landing on Enceladus + Start of in situ research	End of in situ research	Sample retrieve on Earth

Fig. 2. Timeline of the science phase

3.2 *System modes*

The mission concept has eight distinct operation modes.

- Launch mode
- Nominal operations mode
- Science mode : for in situ research as well as orbital scouting for landing terrain
- Safe mode
- Communication mode : for downlink and uplink communication
- Maneuver mode : for orbit insertions, gravity assists and landings
- End-of-mission mode : feezing the lander at the end-of-life
- Emergency mode

3.3 *Contamination control and Planetary protection*

To execute good research on the samples collected on Enceladus, it is needed to avoid any contamination of the samples by terrestrial organisms. In this case, contamination control places more stringent constraints than Planetary Protection policies for the sample collection, study and freight. Landing must as well minimize the likelihood that the spacecraft contaminates the surface and the subsurface ocean for future expeditions. In this case, a likelihood of $1\text{x}10^{-4}$ of contaminating the subsurface liquid ocean is a satisfying threshold for this mission concept.

Contamination mitigation strategies include the use of cleanrooms and ISO class 7 protocols, radiation sterilization from the atmosphere, UV and Saturn magnetosphere exposure, and use of a biobarrier during launch to eliminate as many sources of contaminants as possible from the spacecraft.

4. Systems engineering

In Figure 3 is a high-level mission requirements functional tree. The different components of the tree will be discussed later in the paper.

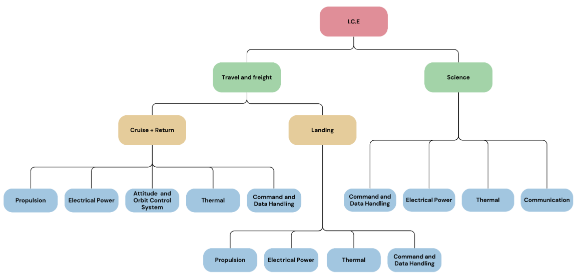

Fig. 3. Functional tree of high-level mission requirements

4.1 *Mission requirements*

- *Sample collection in orbit* : the orbit sample collection system shall collect $10g$ of sample over the 2 year Enceladus orbit ([4] and [5])
- *Sample collection on the surface* : the in situ sample collection system shall collect at least $10mL$ of sample over 2 days (sample quantity needed by the nanopore instrument) ([6])
- *Propulsion* : propulsion shall provide enough thrust to make it to Enceladus and back (for the orbiter and lander first and just orbiter for the return), enough thrust to land on Enceladus (for the lander)
- *Power* : power system shall provide enough power for the cruise and return, science phase from orbit and enough power for the lander to execute in situ research and communicate the results
- *Thermal* : all instruments shall be kept within operating range

4.2 Mission constraints and limitations

4.2.1 Sample contamination

Avoiding sample contamination from Earthly substances is absolutely for good research results. In this way, the collection of the sample has to minimize contamination possibilities, this places an additional constraint on the collection method chosen. Once the samples are collected, they also have to be protected from contamination, this places additional constraints on sample preservation methods.

4.2.2 Landing site selection

Three major constraints have been identified for landing selection :

- *Slopes* $< 10°$: The lander design is robust against tipping and slipping on slopes less than 10. Slopes can be measured my laser altimetry and stereo imaging.
- *High plume fallback* : Lander design has both active and passive sample collection system, plume fallback needs to be high for the passive collection device to gather enough resources for good measurements ([7]).
- *In view the Sun and Earth* : Landing site has to be in view of the Sun for good imaging from orbit and once landed. Landing site has to be in view of Earth for good communication with ground sector([7]).

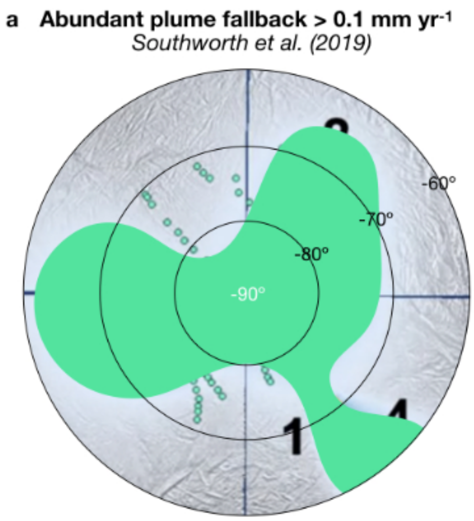

Fig. 4. Abundant plume fallback, in teal is a region satisfying the requirement

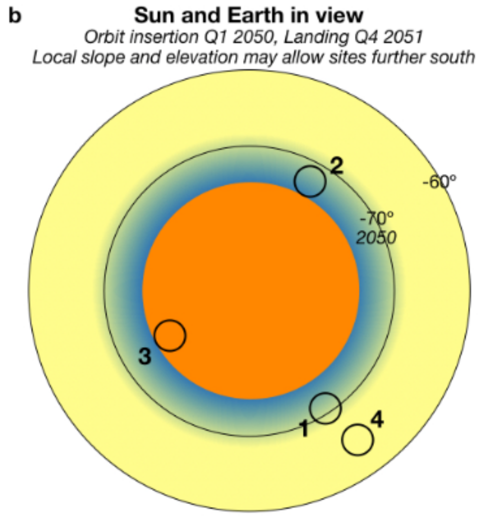

Fig. 5. Sun and Earth in vuew, in orange is a region that does not satisfy the requirement

Regions with slopes of under 10° are not included in Figure 4 and Figure 5 as they would be found via terrain-relative navigation.

4.3 Measures of effectiveness

4.3.1 Success definition

Success of the mission is defined as the return of at least 8g of plume sample. This means that retrieving the sample is the most critical part of the mission. Landing of the in situ research center as well as life detection on Enceladus surface are additional missions added to the original frame of the sample retrieve mission concept.

4.4 Mission milestones' effectiveness

Mission Milestone	Success definition	Success rate
SOI (going)	Inserted in Saturn orbit	0.99
EnOI	Inserted in Enceladus orbit	0.99
Orbit Sample Collection	Collection of 8g of sample	0.85-0.95
Spacecraft Separation	Return capsule separated from lander without failures	0.95
SOI (return)	Inserted in Saturn orbit	0.99
EOI (return)	Inserted in Earth orbit	0.99
Enceladus Landing	Succesfully landed on Enceladus in the right orientation	0.75-0.85
Surface Sample Collection	Collection of 10mL of sample on two day period	0.85-0.95
In Situ Research	Plausible results from Life Detection Suite	0.98

Fig. 6. Major mission milestones' success rates and success definitions (in *green* is the main mission frame and in *yellow* are the additional mission goals)

In Figure 6 is the success rate of major milestones of the mission concept. Success rates were defined in accordance with the risk description table where the likelihood of a risk **(L)** depends on its success rate.

4.5 Interfaces analysis

The different interfaces between the subsystems are described in Figure 7. (1) is a structural interface, (2) is a power interface, (3) is a communication and data interface.

Interface	Propulsion	Thermal	AOCS	Communication	Antennas	Power	Science	Structure
Propulsion		1	3			2		1
Thermal	1					2	2	1
AOCS	3			3	3	2		1
Communication			3		3	2	3	1
Antennas			3	3		2	3	1
Power	2	2	2	2	2		2	1
Science		2		3	3	2		1
Structure	1	1	1	1	1	1	1	

Fig. 7. N2 interface matrix

5. Mission architecture

5.1 Heritage and reference missions

- *Cassini-Huygens mission* : Cassini–Huygens, was a space-research mission by NASA, the European Space Agency (ESA), and the Italian Space Agency (ASI) to send a space probe to study the planet Saturn and its system, including its rings and natural satellites. This space mission discovered the presence of an warm subsurface ocean on Enceladus which is the driving factor for our mission concept.
- *Orbilander flagship mission [6]* : The Enceladus Orbilander is a flagship mission concept created for the 2023–2033 Planetary Science Decadal Survey. Orbilander takes full advantage of the opportunity provided by Enceladus' plumes to search for signs of life. A single spacecraft both orbits and lands, capturing samples from four distinct reservoirs offered by the plumes.
- *Van Allen Probes (VAP)* : the linear sequential shunt system used during this mission is used for this mission concept.

5.2 Risk analysis

Five main risks were determined and graded according to a Likelihood (L) and a Consequences (C) factor in a range from 1 to 5. The cited risks can be seen in the table of Figure 8.

The Likelihood and Consequences factors on the right of the table are the factors after having applied the mitigation strategies.

The principal objective of this mission concept is to retrieve a researchable of the plumes vented out by Enceladus. Taking this into account, preventing the samples from being contaminated is a critical part of the mission

Risk ID	Risk	L	C	Mitigation	L	C
R1	Strict contamination requirements can not be maintained then sample return and science phase on Earth is affected	2	5	a) Use of a bio barrier b) Plan a rigorous cleanliness program	1	5
R2	If autonavigation can not handle closely spaced events of moon tour then the orbit pump-down will be affected	2	4	Pre-loaded backup burns	2	2
R3	If plume density is less than expected then the quality and overall usability of the samples is affected	1	4	Use high precision imaging to assess plume activity	1	3
R4	If landing is not successful, then the entire in situ research phase is affected	3	3	a) Emphasize on landing site reconnaissance b) Conduct landing sequence simulations	1	3
R5	If a safe landing site is not found during the reconnaissance phase, then the entire in situ research phase is affected	2	3	a) Stay in orbit for the whole mission b) Schedule margin to extend the in orbit science phase	2	1

Fig. 8. Risk description table

design. Contamination of the samples during collection or freight back to Earth would mean the fail of the whole mission. The risk **R1** in Figure 8 hence has a consequences factor of 5.

As with any surface-exploring mission, landing is a critical event that comes with inherent risks (**R4**, **R5**), hence the importance of defining a safe landing site during the in orbit reconnaissance phase. In the case of an unsuccessful landing, Planetary Protection policies still have to be respected, this is taken into account in section 3.3.

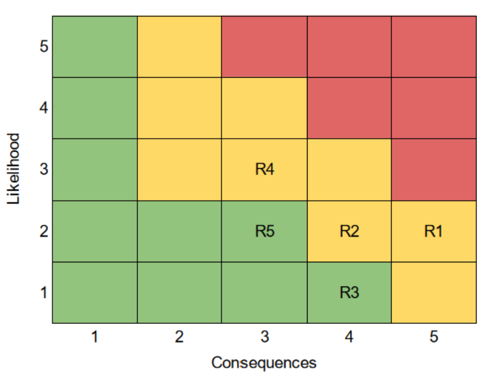

Fig. 9. Risk analysis matrix : High risks are red, Medium risks are yellow, Low risks are green

6. Baseline Design

6.1 Payload instruments

Payload elements		Mass (30% cont) (kg)		Power (40% cont) (W)		Data
		CBE	MEV	CBE	MEV	Minimum total (Gb)
Life Detection	HRMS	20	26	70	98	5.8
	µCE-LIF	3.8	5	5.7	8	0.002
	Microscope	3	4	15	21	0.33
	Nanopore	3.8	5	5	7	6.0
Reconnaissance	Laser altimeter	7	9	17	24	1.3
	Narrow angle camera	20	26	5	7	53
In situ	Seismometer	5.4	7	4.3	6	0.69
	Context imager	3.8	5	12.1	17	1.62

Fig. 10. Payload instruments mass, power and data

6.1.1 Life Detection

- *HRMS* : the High Resolution Mass Spectrometry instrument provides detailed information about the mass of ions in a sample, allowing the identification and characterization of compounds with a high level of accuracy and precision. It requires ice grains from plume fallback. It is used to characterize the bulk organic function from plume.

- *μCE-LIF* : modular instrumentation for capillary electrophoresis with laser induced fluorescence detection offers a versatile and adaptable platform for the separation and analysis of various compounds, particularly those labeled with fluorescent markers. It requires ice grains from plume fallback. It is used to characterize the bulk organic function from plume.

- *Microscope* : the microscope is used to search for evidence of cell-like morphologies. It requires ice grains from plume fallback.

- *Nanopore* : Nanopore technology offers advantages in terms of its ability to analyze individual molecules in real-time, making it a powerful tool. It requires at least $10mL$ of ice sample. It is used to investigate the presence of polyelectrolytes.

6.1.2 Reconnaissance

- *Laser altimeter* : It is used to determine the terrain topography at the south pole to scout for a suitable landing site.

- *Narrow angle camera* : It is also used to determine a suitable landing site as well as active sampling with sub-meter imagery.

6.1.3 In situ

These instruments are used to investigate the science objectives of section 2.2.

- *Seismometer* : It is used to determine the physical as well as chemical environment of the subsurface ocean.

- *Context imager* : It is used to investigate the internal structure of Enceladus using color and mm resolution.

6.2 Propulsion

The spacecraft is divided in two parts : one part will act as the orbiter and return capsule, the other will act as the lander. Hence the propulsion system is also divided in two parts.

The main propulsion system consists of two main bipropellant (N_2H_4/NTO) apogee engines, eight 22 N monopropellant (N_2H_4) steering thrusters and sixteen 4.4 N monopropellant (N_2H_4) attitude control thrusters. The baseline propellant load is 7320 kg of usable propellants to deliver 4600 m/s of ΔV. Propellants are stored in two cylindrical titanium tanks with spherical caps, one for Hydrazine (N_2H_4) and one for Nitrogen Tetroxide (NTO). The maximum expected operating pressure for the mission is 250 psi.

The landing propulsion system consists of a main bipropellant apogee engine and eight monopropellant attitude control engines. The propellant load is 175 kg of usable propellants to provide 100 m/s of ΔV required for landing.

6.3 AOCS

The Attitude and Orbit Control System (AOCS) selected provides three-axis stabilization. The attitude knowledge is acquired via two Star Tracker (ST) as well as one Inertial Measurement Unit (IMU). Three reaction wheels guarantee control with a fourth one available as a spare.

If adjustments to the ΔV are needed, they are implemented by the main bipropellant thrusters. The spacecraft has a total of six wide angle navigation cameras with four of them providing coverage for station keeping and the last two are placed on the lander to be used for hazard avoidance during landing sequence. Attitude and rate knowledge during landing sequence is given by downward-facing cameras providing position and velocity measurements.

6.4 Electrical Power

The Electrical Power System (EPS) provides power generation and energy storage for all mission phases, it is designed to provide 30% margin in all load cases.

Three RTGs provide power to the entire vehicle, two are placed on the orbiter and one on the lander. Together, the RTGs provide 1200W of power when initially loaded with fuel and have an reference decay rate of 1.73% per year. This means the two RTGs on the return capsule are expected to provide 499W at EOM (27 years).

The RTGs ouptput power is regulated by a linear sequential shunt system, that also provides battery charge control. Excess RTG power is dissipated through two sets of shunt resistors that provide thermal energy to the other systems of the spacecraft.

Energy storage is provided on the orbiter by 5 series-connected 42 Ah large-format lithium ion-cells providing 29 Ah. Energy storage on the lander is provided by 3 series-connected 42 Ah ion-cells similar to the ones on the orbiter providing 17.25 Ah. These batteries supplement the RTGs during high-power modes seen in Figure 11.

As seen in Figure 11, the spacecraft has sufficient power margins with the electrical power system cited above.

Subsytem	SOI (7 yrs)	SOI Return (18 yrs)	Landing (14 yrs)	EOI (27 yrs)
Instruments	20	20	20	20
Propulsion	450	380	210	320
Thermal	40	40	40	40
Power	20	20	20	20
AOCs	150	135	120	130
Communication	120	120	120	120
Total	800	715	530	650
Margin (30%)	240	215	159	195
Total + Margin	1040	930	689	845
Power available from RTGs	1064	584	313	499
Battery capacity required (Ah)	-	12.0	13.0	12.0
Battery depth of discharge	-	42.8%**	75.36*	42.8%**

Fig. 11. Electrical power requirements during high-power modes (*Batteries on lander, **Batteries on orbiter/return capsule)

6.5 Thermal

All electrical power produced by the RTGs that is not used by the spacecraft components is assumed to be transformed in thermal energy, either for heating the components via shunters or for rejection via radiators.

Majority of the components are internally radiatively coupled through high emmisivity coating (black paint). The conduction of the heat is done heat pipes, thermal straps and doublers.

Multilayer insulation (MLI) blankets cover the entire spacecraft keeping all the components in a operating range of -30°C to 50°C upon arrival in Enceladus orbit. Some science instruments on the lander need to operate above 0°C, to ensure this, these components are placed in the vicinity of each other so that the whole volume can be easily heated by the shunted RTG.

Additionally, the tanks are covered in 20 layers of MLI and are thermally isolated from the spacecraft. Similar to the tanks, the engines are also thermally isolated from the main spacecraft structure.

6.6 Communication and Command Data Handling (CDH)

The mission concept two distinct communication bands. Uplink will be operated on the X-band and downlink will be operated on the Ka-band. The downlink operated on the Ka-band is primarily data from science executed on the spacecraft and on the surface. Downlink from the spacecraft on the X-band is also provided for maneuvers such as orbit insertions and landing. The Ka-band for the science downlink was selected because of its significant improvement in scientific data return for a slight mass and cost increase.

The lander has four 2.1m parabolic dish HGA antennas and the orbiter has one more of the same type. This is a mass-efficient solution for the data return needs of the science phase.

The data rates needed and storage needs for the whole mission are described in Figure 12.

Command Data Handling	
Flight element housekeeping data rate	4.0 kbps
Data storage capacity	256 Gb
Maximum storage record rate	3000 kbps
Maximum storage playback rate	3000 kbps

Fig. 12. CDH characteristics table

6.7 Structures and mechanisms

The payload can be defined in three main parts : a mechanical structure, a return capsule and a lander. The lander structure has an dry mass of 230 kg, and the return capsule a dry mass of 640 kg. Finally, the mechanical structure ,including the two main thrusters and propellant tanks, that connects the return capsule and the lander has a dry mass of 870 kg.

6.7.1 Mechanisms

- *Spacecraft Separation Mechanism (SSM)* : the SSM is provided by **beyond gravity** and will be deployed during the Spacecraft Separation Sequence.

- *Deployable Scoop* : once the lander is on Enceladus surface, sample collection is done by the funnel as well as by a scoop. This scoop is on a deployable arm in order to reach the ground and be able to bring the sample back to the Life Detection Suite.

- *Deployable Antenna* : the antenna placed on the lander is deployable with the use of a robotic arm to keep it from being damaged during the cruise and the landing sequence.

- *Deployable Landing Legs* : just before making contact with Enceladus surface, the lander deploys landing legs for a smooth landing.

6.8 Summary

In Figure 13 is the mission concept mass budget by subsystem.

Subsystem	Mass (kg)
Propulsion	535
Mechanical structure	870
Lander	230
Instrument Payload	103
Power	261
Thermal	140
Communication	68
Total Dry Mass + 30% Margin	**2870**
Usable Hydrazine	4734
Usable Nitrogen Tetroxide	2916
Total Wet Mass	**10520**

Fig. 13. Mission mass summary

The key trades of the concept development phase are summarized in the table of appendix 1.

7. Major mission sequences

7.1 Spacecraft separation sequence

Separation of the lander and the return is done by the SSM component provided by **beyond gravity**. Once sample collection as well as landing site reconnaissance is finished, the SSM mechanism will separate the lander from the return capsule. Once this is done the return capsule executes an Orbit Exit maneuver and makes its way to Saturn for SOI. The lander starts the landing sequence as soon as it is detached from the return capsule.

7.2 Landing sequence

As soon as the lander separates from the return capsule it will start to make its way to Enceladus surface. This starts with a Descent Orbit Insertion maneuver executed at apoapsis to target a 5-km altitude at periapsis. Once the 5-km altitude is attained, the lander moves towards its determined landing site using Terrain Relative Navigation.

Once in a 200 m radius of the landing site, the lander descends to an altitude of 250 m to scout for slopes of under 10° near the landing site. Once the final landing site is determined, the lander descends to an altitude of 10m. To avoid sample collection contamination, the main thruster powers up for 5s, once this is done, the steering thrusters will translate the robot's position by 25m horizontally. Once the horizontal velocity is stabilized, the landings legs deploy and the lander makes its way to the ground for a smooth landing. Once on Enceladus surface, the robotic arm as well as the parabolic antenna are noth deployed to get the lander in operational mode.

8. Spacecraft configuration

8.1 Return capsule configuration

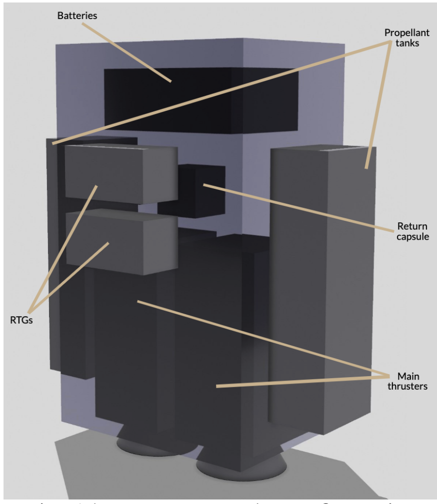

Fig. 14. Return capsule configuration

8.2 Lander configuration

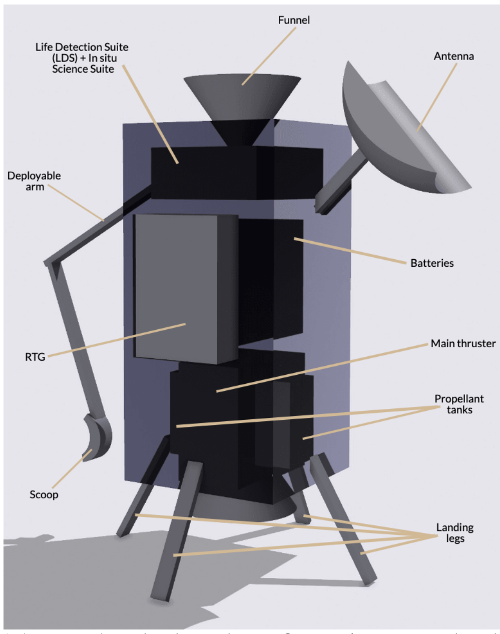

Fig. 15. Lander deployed configuration once landed on Enceladus

8.3 Cruise configuration

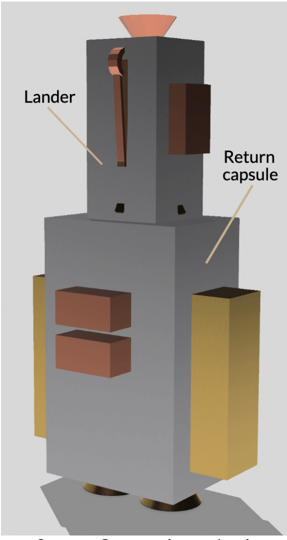

Fig. 16. Spacecraft configuration during cruise to Enceladus

9. Conclusions

In summary, the endeavor to secure a sample from Enceladus through a space mission marks a significant leap in the search for extraterrestrial life. The exploration of the astrobiological potential within Enceladus, particularly its sub-surface ocean, presents a captivating and exciting scientific goal. This paper has delved into crucial aspects essential for the feasibility of a space mission of such type. While it is clear that further in-depth studies are imperative for the realization of this mission, this paper serves as a promising initiation point for subsequent research and development on the subject.

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EPFL

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Trade Study	Options Considered	Selected option	Rationale
Propulsion	Electrical propulsion Chemical propulsion	Chemical propulsion	Most mass-efficient and simplest approach. High thrust-to-weight ratio required during landing sequence.
Attitude control	Reaction wheels Thrusters	Reaction wheels	Method saving the most propellant while meeting the requirements
Orientation	3-axis stabilization Spin stabilization	3-axis stabilization	Orientation has to be controlled on 3-axis during significant portions of the orbit, science phase and landing sequence. Spinning is only an option during cruise.
Electrical power	RTGs Solar arrays	RTGs	Enceladus is too far from the Sun to use solar arrays (only feasible use in the orbit of Jupiter). Mass-efficient solution for providing power to Saturn orbit.
Telecom band	X-band only X-band + Ka-band	X-band + Ka-band	Significant improvement in science data return for a low mass and cost increase.
Antennas	Parabolic dish Antenna array	Parabolic dish	Most mass-efficient solution to meet data return needs.
Contamination control	Biobarrier Cleanliness protocols	Cleanliness protocols and biobarrier	Avoiding contamination of the samples is absolutely critical so inplementation of a combination of different contamination control seem in order.
Launch vehicle	SLS Block 2 Falcon Heavy	SLS Block 2	Enables direct trajectory with a Jupiter flyby.
Lander configuration	Deployable landing legs Horizontal orientation Vertical orientation	Deployable landing legs Vertical orientation	Most robust and simple solution considering the variability of the surface terrain
Spacecraft configuration	Lander on top of orbiter Lander on side of orbiter	Lander on top of orbiter	Can use the funnel of the lander to collect the samples from orbit and then use it to collect plume fallback on surface

Fig. 17. Key trades of mission concept