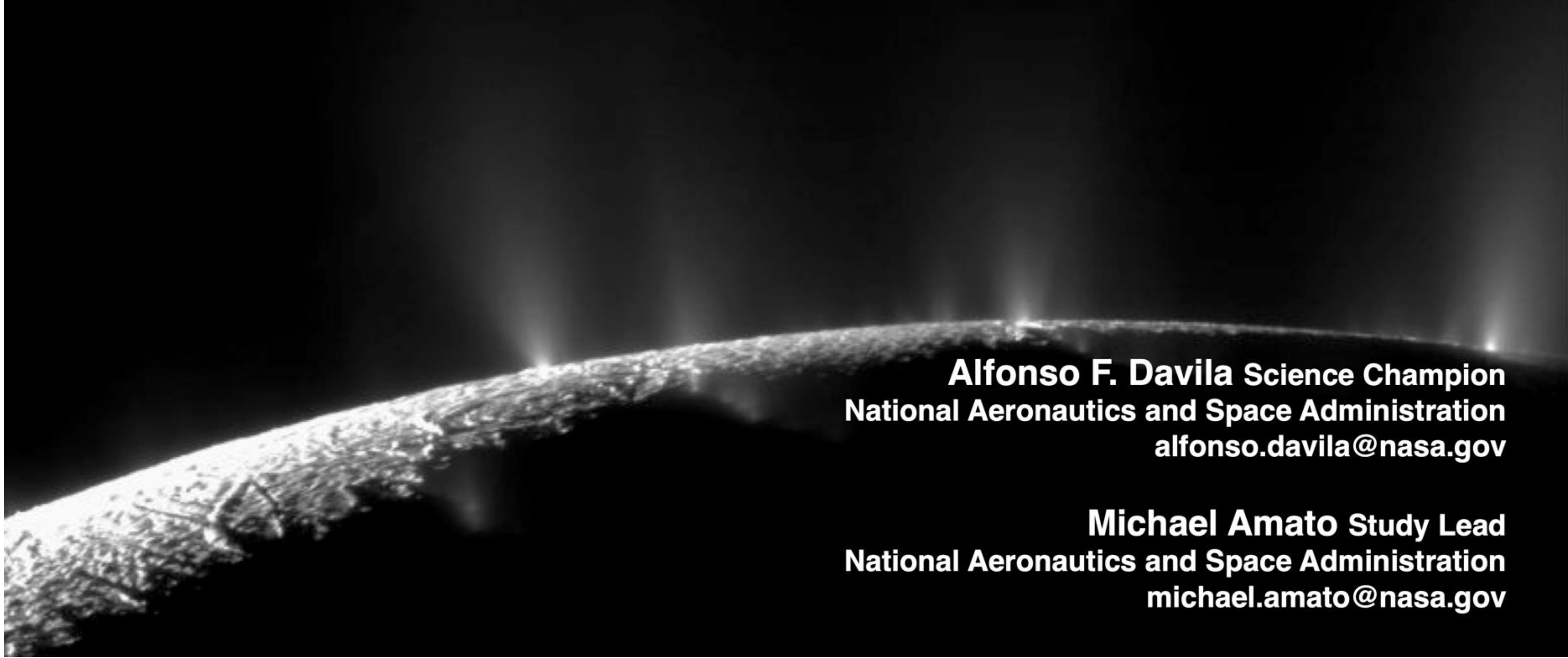
ENCELADUS MULTIPLE FLYBYS

PLANETARY MISSION CONCEPT STUDY FOR THE 2023–2032 DECADAL SURVEY

IS THERE LIFE BEYOND EARTH?



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Planetary Science Decadal Survey
Enceladus Multiple Flybys Mission Concept Design Study Final Report

Executive Summary

Finding evidence of life beyond Earth would be an extraordinary society-shaping event. Thanks to discoveries made by the *Cassini* spacecraft at Enceladus during the last decade, we are now poised to address the question “are we alone?” with scientific rigor. The Enceladus Multiple Flybys (EMF) mission concept demonstrates that such paradigm-shifting science can be accomplished at this unique destination with existing technology and within the resource envelope of NASA’s New Frontiers program.

During the last decade, *Cassini* established that Enceladus hosts a global subsurface ocean of liquid water; found evidence of ongoing hydrothermal activity at the ocean floor; detected bioessential elements and a source of chemical energy that life can exploit; confirmed that the pH, temperature, and salinity of the ocean fall within the habitable range for Earth-like microorganisms; and discovered complex organic molecules, ‘the stuff of life’, in ocean samples. Many of these discoveries were made possible by the existence of a plume of icy particles and gas emanating from Enceladus’ South Polar Terrain (SPT). The plume contains ocean materials that are venting into space through a system of cracks in the ice shell, making fresh ocean material available to an orbiting spacecraft, without the need to land, dig or drill. Of all solar system destinations explored to date, Enceladus clearly has the highest biological potential and provides the easiest path to search for evidence of an alien biosphere.

Following on *Cassini*’s steps, the EMF mission would return to Enceladus and repeatedly fly though the heart of the plume at speeds ≤ 4 km/s and ≤ 50 km elevation, carefully collecting ocean samples to search in them for multiple, independent signatures of life with proven and mature instruments. In addition, sensitive sensors would characterize the chemistry of the ocean with unprecedented detail, while remote sensing cameras would characterize the plume and the surface thermal environment to better understand how ocean materials are ejected into space. To achieve its science objectives, the EMF mission would follow stringent contamination control methods, taking advantage of recent technology developed with New Frontiers program funds. With a 12-year mission duration, EMF could launch in the 2030s and deliver ground-breaking science in the 2040s.

Two existing EMF mission concepts, designed and costed independently and proposed to the New Frontiers 4 opportunity, offer diverse trajectory options, multiple spacecraft and payload alternatives, and distinct concepts of operations, compatible with the schedule and cost constraints of the NF program. One of those concepts, which captures months of mission concept development, comprehensive trade studies, and cost analyses by a dedicated and experienced team of scientist and engineers, served as a reference for major sections of this report. That mission did well in the review areas under the New Frontiers 4 opportunity and received a Category 2 ranking reserved for ‘well-conceived and scientifically or technically sound investigations which are recommended for acceptance’.

Armed with mature technology, a compelling mission concept and a strong scientific foundation, EMF can finally take advantage of the tremendous opportunity presented by Enceladus to address a history-defining question: Is there life beyond Earth?

1.0 Scientific Objectives

1.1 Science Motivation

Are we alone? Whether life exists beyond Earth remains a fundamental question driving our exploration of the solar system. A positive answer would be as significant to humanity as Copernicus' discovery of a heliocentric Solar System, bringing a fresh perspective on biology, not as a local anomaly unique to our planet, but as a true cosmic phenomenon.

Of all solar system environments explored to date, Enceladus, a small moon of Saturn, has the highest potential to host an extraterrestrial biosphere. NASA's *Cassini* spacecraft discovered a global subsurface ocean of liquid water beneath the moon's icy surface (Iess et al. 2014; Thomas et al. 2016) and established that the ocean is a habitable environment for life, as we know it (McKay et al., 2014). A follow-up mission that seeks to find evidence of life in Enceladus' ocean could yield the most impactful scientific result in history. Such a mission is possible with current technology and under the cost cap of NASA's New Frontiers program, which puts Enceladus in a central role as a pathfinding destination to test Ocean World exploration strategies that minimize the scope and cost of missions needed to address the momentous question—Is there life beyond Earth? (Hendrix et al., 2019).

The plume

Enceladus ocean materials are accessible to an orbiting spacecraft thanks to a large plume of icy particles and gases emanating from the moon's SPT (Porco et al., 2006) (**Figure 1**). The *Cassini* spacecraft characterized the plume during multiple flybys above the SPT, establishing its structure, chemical composition, and origin (Hansen et al., 2011; Khawaja et al., 2015; Postberg et al., 2011; Postberg et al., 2018; Waite et al., 2017; Waite et al., 2009). Data obtained by *Cassini* revealed that the plume's icy grains largely consist of frozen droplets of ocean water (Postberg et al., 2009) emanating from a system of vents (the so-called Tiger Stripes), which are the surface expression of large cracks that penetrate into the moon's icy crust, communicating the top of the subsurface ocean with the environment of space. The plume is structurally complex (Hansen et al., 2011; Porco et al., 2014, 2017; Spitale et al., 2015). Its structure results from two main sources of materials: a system of >100 discrete 'jets' of icy particles expelled through the Tiger Stripes (Porco et al., 2014); and more diffuse emissions of vapor called 'curtains' (Spitale et al., 2015). Jets are thought to be made primarily of ocean materials, whereas curtains are thought to be made primarily of water vapor emanating from the surface and near subsurface of the moon's icy crust.

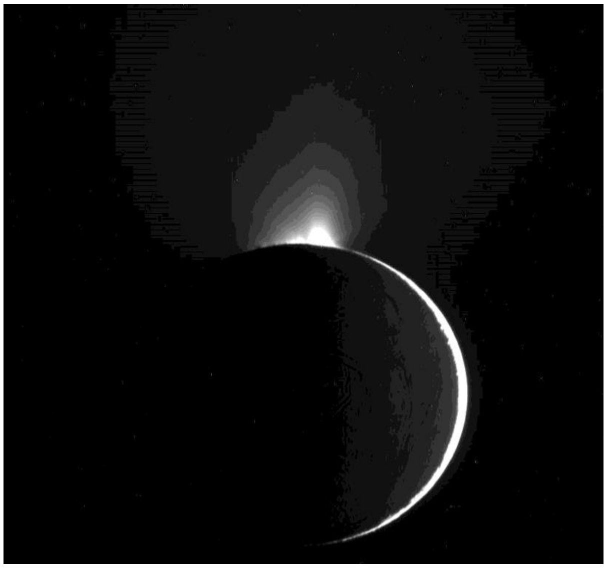

Figure 1. The Enceladus plume allows to study ocean materials from an orbiting spacecraft, thus enabling life-detection science with a New Frontiers-class mission. Image: NASA/JPL.

The plume enables sampling and investigation of the subsurface ocean without the need for landing and deep drilling. Instead, the plume can be sampled periodically by a spacecraft that orbits around Saturn, as was established by *Cassini*. These important considerations reduce mission complexity, risk and cost, making Enceladus a viable destination to search for evidence of life under the constraints imposed by NASA's New Frontiers program.

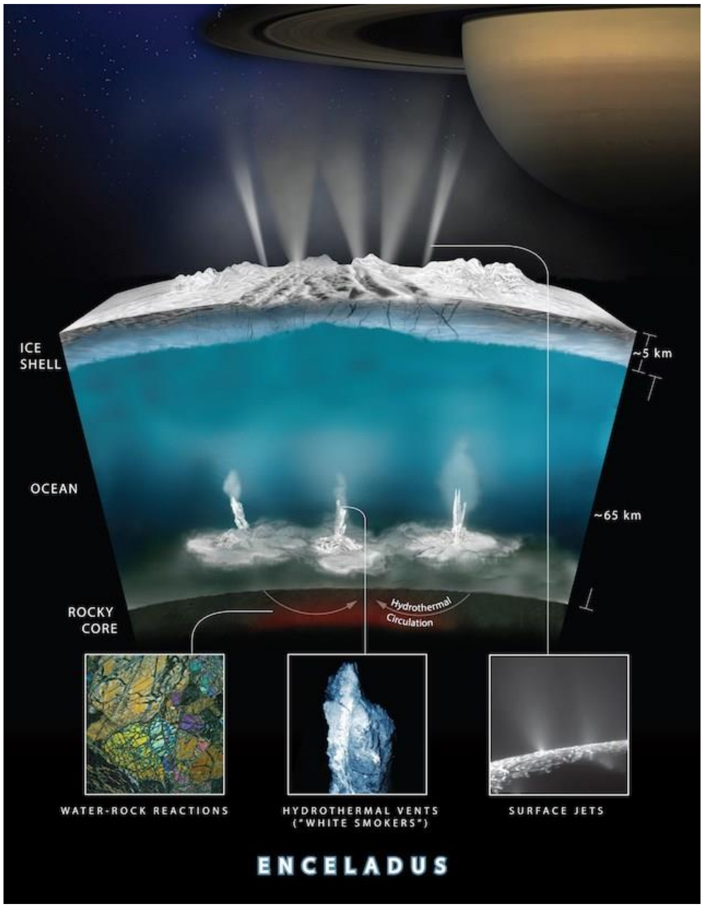

Figure 2. Enceladus is the only body besides Earth known to simultaneously satisfy all of the basic requirements for life as we know it. Image: NASA-GSFC/SVS/NASA/JPL-Caltech/SwRI.

The ocean

Cassini's investigations of the Enceladus plume indicate that the key elements for habitability—liquid water, essential elements, and chemical energy—are co-located at Enceladus; and that physicochemical conditions (e.g., temperature, pH, salinity) are within the habitable range (Glein et al., 2015; Hsu et al., 2015) (**Figure 2**). The Enceladus ocean is global (depth ~ 65 km) and long-lived (Iess et al., 2014; Thomas et al., 2016). Essential elements such as Carbon, Hydrogen, Nitrogen, Oxygen and Sulfur (collectively known as CHNOS) exist in organic or inorganic compounds (Khawaja et al., 2015; Postberg et al., 2009, 2018; Waite et al., 2009, 2017). Phosphorous (P), which is essential for terrestrial life, has not yet been detected—although its presence is expected based on the ubiquity of P-bearing minerals in solar system materials (Pasek & Lauretta, 2005). In addition, hydrogen gas (H_2) and carbon dioxide (CO_2) detected in plume materials (Waite et al., 2009, 2017) form a chemical redox couple that ocean microorganisms could exploit as a source of energy, analogous to methanogenic archaea on Earth. The range of temperatures estimated in the ocean (0ºC in the water column to c.a. 100ºC in the sediments, Hsu et al., 2015), the ocean's salinity (~2%, similar to Earth oceans) and its pH (8-10) are compatible with the stability of biomolecules such a lipids, proteins and nucleic acids. Indeed, NASA's Roadmap to Ocean Worlds (ROW) states that the habitability of Enceladus' ocean has been sufficiently established based on *Cassini* measurements (Hendrix et al., 2019), making Earth and Enceladus the only locations known so far where biology-friendly conditions currently exist.

The hydrothermal vents

Cassini discovered evidence of ongoing hydrothermal activity at the ocean bottom (Hsu et al., 2015). The chemistry of plume materials is consistent with the presence of alkaline hydrothermal vents resembling the Lost City vents in the Atlantic ocean. Far-from-equilibrium conditions in alkaline hydrothermal vents satisfy thermodynamic constraints and provide continuously reactive chemical environments (e.g., Lane et al., 2010) making these environments an engine of chemical disequilibrium at Enceladus (Glein et al., 2015) that life can exploit for growth and reproduction. In addition, alkaline hydrothermal vents represent a possible location for prebiotic chemical evolution, and a leading hypothesis in origins of life research favors alkaline hydrothermal vents as the most likely site of the transition from geochemistry to life (Lane & Martin, 2012; Martin & Russell, 2007; Russell et al., 1993). Thus, Enceladus also offers a unique opportunity to address specific hypothesis regarding the sequence of chemical steps that could have led to the origin of life on Earth, and on other worlds with similar hydrothermal environments.

1.2 Science Objectives

ROW recognizes that 'a search-for-life mission could be sent as a next step', and 'strongly recommends that a search-for-life mission at Enceladus be of high priority in the next decade (Hendrix et al., 2019). This ultimate goal can be accomplished with the following science objectives of the EMF mission:

Objective 1. Search for signs of life in Enceladus plume materials. Is Enceladus inhabited? This is one of the most compelling and challenging scientific questions in planetary sciences. A convincing answer requires searching for multiple features of life (biosignatures) with repeatable measurements (e.g., Neveu et al., 2018). Multiple, independent measurements of molecular qualities in organic compounds including, but not limited to, abundance distributions, molecular structures and molecular patterns, are a sound and often recommended life detection strategy (Hand et al., 2017; NASEM, 2019) (**Figure 3**). Organic biosignatures detectable at trace levels with high-TRL instruments are of special interest and well-motivated by *Cassini*'s detections of numerous complex organic species. The highest science return will result from targeting organic compounds that are expected to be present both because of their prevalence and key roles in Earth's biology, and also because of their widespread occurrence in abiotic systems, and in models of prebiotic chemical evolution (e.g., lipids, amino acids…). The search for and characterization of such organic compounds will provide important insights regarding the extent of organic chemical evolution in the ocean, whether life ever existed or not.

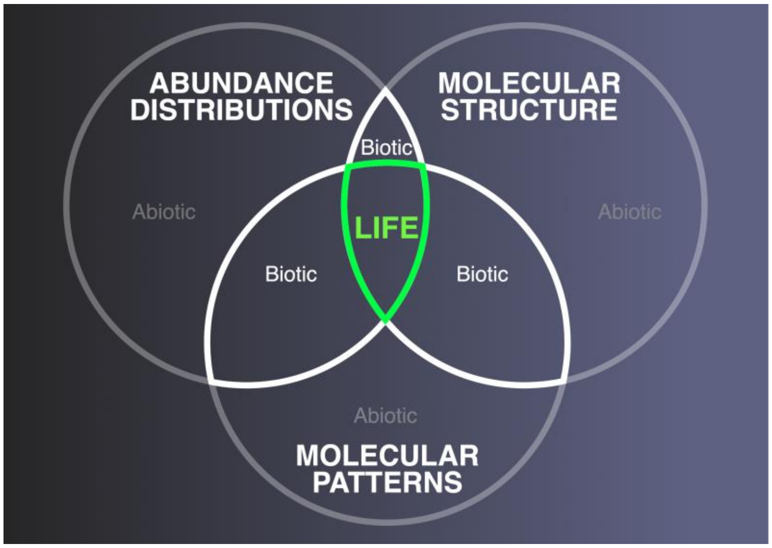

Figure 3. Multiple, independent measurements of molecular qualities can help differentiate between biotic and abiotic sources of organic matter at Enceladus, and potentially provide robust and unambiguous evidence of life.

Objective 2. Assess the habitability of the Enceladus ocean. How habitable is the Enceladus ocean? *Cassini* data has been used to establish that the Enceladus ocean is habitable. But *Cassini* was not designed for quantitative habitability assessments of subsurface oceans—at the start of the *Cassini* mission, the Enceladus ocean and plume had not been discovered. To address this critical question, measurements are needed to refine *Cassini*'s assessment and fill in knowledge gaps on key habitability parameters, including sources of essential elements and micronutrients; sources of chemical energy (e.g., chemical redox couples); and key physicochemical parameters. Such measurements will allow to assess the habitability of the ocean not as a binary factor (either it is habitable or not), but as a quantifiable variable along a spectrum, from more habitable to less habitable. A more quantitative habitability assessment would provide additional constraints on the biological potential of the Enceladus ocean—its potential biological productivity—including the amount of biomass that Enceladus could theoretically support, as well as the types and diversity of organisms that could co-exist (e.g., Cable et al., 2020). This information is important to place the life detection objective into an appropriate environmental context, and specifically it provides critical data to interpret the implications of a negative result for signs of life.

Objective 3. Characterize Enceladus' cryovolcanic activity. What is the nature and origin of Enceladus' cryovolcanic activity? While the search for evidence of life and a more thorough habitability assessment drive the science objectives of the EMF mission, additional characterizations of the Enceladus plume that supplement *Cassini* observations would be desirable. Enceladus' complex cryovolcanic plume is so far a unique planetary phenomenon, but plume-like emissions have been tentatively detected at Jupiter's moon Europa (Jia et al., 2018; Sparks et al., 2017) and Neptune's moon Triton (Soderblom et al., 1990). Therefore, a better understanding of how cryovolcanic activity originates at Enceladus would provide important insights into a phenomenon that could be relatively common in Ocean Worlds. More details regarding the structure of the plume (e.g., a more precise estimation of the relative contributions of jets and curtains to the overall plume based on measurements of gas/grain ratios or grain size distributions) and how it varies in space and time, would help constraint ejection mechanisms, and the relationship between plume activity and orbital parameters.

1.3 Science Payload

The EMF science instruments are tailored to address the top-level science objectives of the EMF mission (see Table 1, Science Traceability Matrix). Additionally, the science payload would include a sample handling system (SHS) to collect icy grains from the Enceladus plume and to deliver the collected sample to each instrument. For the purpose of this report, the science instruments and the SHS represents one approach which is similar to payload approaches which have already been found to fit in the New Frontiers resource envelope, although multiple strategies exist to collect and analyze plume samples (as exemplified by *Cassini*). In addition, the choice of instruments to search for evidence of life is not unique to the EMF mission, and has some overlap with other life detection mission concepts such as the Europa Lander (Hand et al., 2017). This is important because it exemplifies how the search for evidence of life at this particular location can support similar missions at other locations. The specific payload elements to achieve each science objective are as follows:

- **Objective 1** can be accomplished with Organic Chemical Analyzers (OCA) that target specific molecular biosignatures. A combination of instruments that target multiple types of organic compounds independently would be preferred, since the overlapping and complementary capabilities from two independent analytical approaches provide a more robust search for, and interpretation of, biosignatures.

- **Objective 2** can be accomplished with Inorganic Chemical Analyzers (ICA) that target specific CHNOPS-bearing compounds and micronutrients to low (mM to µM) limits of detection and help constrain key habitability parameters from analyses of plume samples. The primary role of the ICA is to measure the relative abundance of a diverse suit of ions commonly used by terrestrial organisms as sources of bioessential elements and micronutrients, as well as to seek potential redox couples, and to further constrain the pH and salinity of the subsurface ocean.
- **Objective 3** can be accomplished with a narrow angle camera (NAC). The NAC would investigate the photometric behavior of the plume at high phase angles (≥ 130º) in a manner similar to *Cassini*. NAC images of the plume and derived plume brightness data, obtained over successive flybys, would be used to model the plume's structure and particle contents based on a suite of physical quantities: the size distribution, and volume number and mass densities per size bin of icy µm-size icy grains, as well as their total abundance (e.g., Porco et al., 2006; 2017).

Additional details of the science payload, including examples of mature instruments that could address each science objective, are provided in Section 3.1.

1.4 Top Level Mission Requirements

There are several top-level mission requirements needed to address the science objectives of the EMF mission:

- **Flyby speed**: *Cassini*'s flybys of Enceladus occurred at speeds in excess of 6 km/s. This was in part motivated by some of the payload instruments (i.e., CDA, INMS), which relied on high speeds to turn plume materials into ionized plasma so they could be detected by the instrument sensors. However, at such high speeds many of the source-diagnostic molecular qualities that can be used to detect signatures of life are obliterated. Therefore, for the EMF mission sampling of the plume must be conducted in a way that minimizes alteration of the target compounds to enable measurement of molecular composition and structure. Recent studies predict that organic molecules collected at speeds ≤ 4 km/s would still preserve the diagnostic traits that are used to assess their origin, biotic or abiotic (Jaramillo-Botero et al., 2021). These speeds would still be compatible with *Cassini*-like CDA- or INMS-type instruments (Srama et al., 2011; Waite et al., 2004) and with other types of OCA such as Separation-Mass Spectrometers (SMS).
- **Multiple flybys**: *Cassini* flew by Enceladus 22 times, sampling and analyzing plume materials and spatially resolving the structure and composition of the plume. This existing data is a significant asset to plan the flyby strategy of the EMF mission. Cassini data shows that only the gas and the smaller icy grains, are ejected into space with enough velocity to escape Enceladus' gravitational pull. While Enceladus' gravity is low due to the moon's small size, it is still sufficient to reclaim some of the ocean materials ejected into space, which fall back to the surface and accumulate across the SPT. Therefore, multiple flybys of Enceladus are needed in order to collect several samples of the plume and obtain statistically significant data of chemical composition. Multiple flybys also afford the opportunity to sample and observe the plume from different vantage points (e.g., different flyby trajectories) helping reveal the spatial heterogeneity of the plume. A high elevation flyby (> 50 km) would be desirable as it would allow to obtain a sample of the plume that is mostly composed of non-

ocean materials, providing a negative control for life signatures. The remaining flybys would occur at ≤ 50 km altitude. Models predict that lower flyby altitudes allow to capture the highest amounts of ocean materials (2-4 µL m^{-2}) (Porco et al., 2017).

- **Contamination control**: Because of the small sample volumes expected to be collected after each flyby, and the low organic content expected in the samples (equivalent to single cell quantities of molecules, see Porco et al., 2017), contamination control is of primary concern. In order to minimize the likelihood of a false positive result the spacecraft and the science payload must be clean of contaminants to extremely low levels, and stringent contamination control requirements must be implemented and validated throughout the lifetime of the mission.

Table 1. The EMF Science Traceability Matrix (STM) science objectives, measurements, and notional instruments are outlined in summary form below.

Science Objective		Measurement	Notional Instrument			
			OCA1	**OCA2**	**ICA**	**NAC**
SIGNATURES OF LIFE	**Obj. 1: Search for evidence of life in Enceladus plume materials**	Relative abundance and structure of molecular biosignatures in ocean materials.	■	■		
OCEAN HABITABILITY	**Obj. 2: Assess the habitability of the Enceladus ocean**	Essential elements & micronutrients; sources of chemical energy and physicochemical parameters	▨	▨	■	
PLUME ORIGIN & STRUCTURE	**Stretch Science Objective: Characterize Enceladus' cryovolcanic activity**	3A. Plume structure including, but not limited to, ice grain size and ice/gas ratio.				■

Organic Chemical Analyzer (OCA); Inorganic Chemical Analyzer (ICA); Narrow Angle Camera (NAC).

2.0 High-Level Mission Concept

2.1 Overview

The enormous success of *Cassini* demonstrates the effectiveness of Saturn orbiters that fly through the plume of Enceladus to collect and analyze plume materials. *Cassini* showed that such plume flybys can be accomplished at different speeds and elevations opening the mission space for other Saturn orbiters that target the Enceladus plume.

Following up on *Cassini*, two mission concepts were proposed in response to NASA's New Frontiers 4 announcement of opportunity (Reh et al., 2016). Both mission concepts were Saturn orbiters flying by Enceladus' south pole capturing plume materials, to search in them for evidence of life and to assess the habitability of the subsurface ocean. One of the mission concepts received a Category 2 ranking (well-conceived and scientifically or technically sound investigations which are recommended for acceptance) and is the basis for this concept report.

Based on this previous experience, the concept maturity level of the EMF mission is at or possibly above CML6. The mission concept has been detailed to the subsystem level and has been shown to meet New Frontiers requirements for mass, power and cost margins. EMF builds upon the mission operations developed for *Cassini*, leverages a validated New Frontiers-class mission concept, and shares some of the science instruments proposed for other life detection missions (e.g., Hand et al., 2017; MacKenzie et al., 2020). Mission and spacecraft design features include:

- Launch between 2031 and 2039 on a Falcon Heavy expendable (ΔV=2 km/s) with a 5 m fairing. Potential for using the Falcon Heavy reusable.
- 12-year mission duration.
- ≤ 100 kg science payload.
- <160 W to power science payload.
- Powered with MMRTGs (waste heat to warm up the spacecraft).
- Optical navigation with Ka-band High Gain Antenna for spacecraft communications.

2.2 Contamination Control and Planetary Protection

To achieve the science objectives, the EMF mission must be designed to minimize and characterize contamination by terrestrial organisms. Contamination control thus places more stringent requirements on the mission than Planetary Protection concerns of forward contamination. The EMF mission is classified as a Category III mission because Enceladus is "of significant interest relative to the process of chemical evolution and/or the origin of life" and landing must minimize the likelihood of "contamination [of the surface] by the spacecraft that could compromise future investigations" (NPR 8020.12D2). The project team developing this mission would have to demonstrate a probability <1x10-4 contamination of liquid ocean. Provisions and mitigations for planetary protection would include use of cleanrooms and ISO class 7 protocols, monitoring and sample collection, material control plans, bakeouts, sterilization from radiation, UV and Saturn magnetosphere exposure, and use of a spacecraft biobarrier during final processing through launch to eliminate as many sources of contaminants as possible from the spacecraft.

2.3 Technology Maturity

The science payload consists of instrument types that have previously flown and require tailoring to the EMF-specific requirements. One new enabling technology (SHS) was included in the design, and its TRL are shown in Table 2. The SHS collects samples of icy grains from the Enceladus plume, enabling Objectives 1 and 2. Development is currently on track for the SHS sub-systems to reach TRL6 under programs like COLDTech, ICEE-2, PICASSO, and MatISSE.

Table 2. Summary of enabling technologies for the EMF mission concept, their TRL, the assignment rationale, and some examples of development efforts currently underway.

Item	TRL	TRL rationale	Example development efforts
Sample Handling System (SHS)	5	Specific implementation for Enceladus environment designed and developed, but flight-qualifying tests remain.	Adams, APL (COLDTech 80NSSC17K0618; NNX17AF48G); Zhong, JPL (PICASSO, 18-PICASO18_2-0106); Short, SRI (PICASSO, 80NSSC17K0096); Malespin, NASA GSFC (ICEE2); Ricco, NASA Ames (PICASSO); COLDTech (NNX17AK36G); Bourouiba, MIT (PICASSO, 80NSSC20K1092)

2.4 Key Trades

Several trade studies were conducted by the design team for major design decisions. The best solutions were selected for the mission concept using a combination of mission performance requirements and engineering judgement of the technical benefit, cost, schedule, and risk trade-offs. Major system and subsystem design decisions are described in Table 3.

Table 3. System-level trades during concept development

Trade Study	Options considered	Selected approach
Power source	• Solar arrays • MMRTG or newer RTG	*MMRTG or newer RTG*: Most mass-efficient solution for providing power at Saturn distance.
High gain antenna (HGA)	• Parabolic dish • Antenna array	*Parabolic dish*: Most mass-efficient solution for data return to meet science needs.
Contamination control and planetary protection	• Cleanliness protocols • Pre-launch sampling	All cleanliness protocols will be used to reduce bioburden to acceptable levels; sampling during I&T
Launch vehicle	• Falcon Heavy • Atlas V551	Falcon Heavy expendable

3.0 Technical Overview

3.1 Instrument Payload Description

The candidate EMF mission concept payload is selected to meet the requirements of the Science Traceability Matrix while also satisfying additional mission constraints such as total mass and power consumption (Table 4). Examples of candidate instruments suitable for the EMF mission concept are provided in the flagship mission concept "Enceladus Orbilander" developed as a Planetary Mission Concept Study for the 2023-2032 Decadal Survey (MacKenzie et al., 2020) and in the "Europa Lander Science Definition Team Report" (Hand et al., 2016). Many of the example instruments are based on recently flown hardware. Some of the example instruments might require modifications to meet the environmental conditions, sensitivities, fields of view, etc. needed to address the mission requirements of the EMF mission. Many of these payload elements have been matured since the New Frontiers 4 call through various programs:

- *Organic Chemical Analyzer (OCA)*: Characterizes simple and complex organic molecules present at sub-ppb concentrations in plume samples (Objective 1) (Porco et al., 2017; Steel et al., 2017). A defining feature of this instrument, or combination of instruments, is its capability to discriminate between compounds based on their structure or molecular weight, enabling identification of individual molecules and molecular weight distribution patterns by mass spectrometry over a wide effective dynamic range. This capacity to 'tease out' different organic molecules must surpass the performance of the Ion and Neutral Mass Spectrometer (INMS) (Waite et al., 2004) and the Cosmic Dust Analyzer (CDA) instruments on *Cassini* (Srama et al., 2004). Several mature options exist as model instruments, including Separation-Mass Spectrometers (SMS) that chemically separate molecules prior to identification based on their mass spectra; Electrochemical Organic Detectors (EOD) that identify individual organic molecules based on structural properties; or High-Resolution Mass Spectrometers (HRMS) that use very high resolution mass spectrometry to discriminate molecular functional groups and molecular weight distribution patterns. Depending on the resources of the EMF mission, more than one OCA could be flown. For the point design of the EMF mission concept, two OCA instruments were assumed as a stress-case.

- *Inorganic Chemical Analyzer (ICA)*: Characterizes the physical and chemical environment of the ocean by measuring inorganic species and constraining key habitability parameters in plume samples (Objective 2). Of particular interest would be ICAs that can detect compounds that contain elements needed to build cellular components (e.g., Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorous, Sulfur) at mM concentrations, as well as a diverse set of micronutrients (e.g., Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}…) at sub-mM concentrations. In addition, the ICA should be able to obtain evidence of possible redox pairs that life could exploit (in addition to the CO_2/H_2 pair detected by *Cassini*). Finally, the ICA should obtain data that allow estimates of the pH and the salinity of ocean materials more accurate than those derived from *Cassini* data (Glein et al., 2015). Collectively, this wealth of chemical information would help refine how much biomass the ocean could support and therefore how much biological signal one might expect in the plume samples (Cable et al. 2020). Several mature options exist as model instruments, including dust analyzers similar to the CDA instrument flown on *Cassini* (Srama et al., 2004), and Electrochemical Sensor Arrays (ESA) equivalent to the Wet Chemistry Lab (WCL) flown on the Mars Phoenix lander (Kounaves et al. 2010).

- *Narrow Angle Camera (NAC)*: The NAC provides sub-m resolution imaging required to characterize surface topography and surface expression of the vents (Objective 3). The NAC ought to be able to resolve the structurally complex nature of the plume (Porco et al., 2006; 2017; Hansen et al., 2020), which results from two main sources of materials: (1) a system of dozens of discrete 'jets' of icy particles and gas emanating from the Tiger Stripes (Porco et al., 2014); and (2) more diffuse emissions of vapor called 'curtains' (Spitale et al., 2015). Jets are thought to be made primarily of ocean materials, whereas curtains are thought to be made primarily of water vapor emanating from the surface and near subsurface of the moon's icy crust. Understanding the relative contributions of jets and curtains to the overall plume (e.g., through measurements of gas/grain ratios; grain size distributions…) and their temporal and spatial variability, would help determine how plume samples may have changed since synthesis in the ocean through ascent and ejection, thereby allowing the inference of subsurface conditions from plume measurements. Several mature options exist as model instruments, such as the LORRI camera (Cheng et al. 2009) on New Horizons, which has sufficient resolution in a compact thermal design.

In addition, the EMF point design includes a SHS to collect icy grains from the Enceladus plume and to deliver the collected sample to the OCA and the ICA instruments.

Table 4. EMF instrument CBE characteristics.

Item	OCA1	OCA2	ICA	NAC	SHS
Size/dimensions (cm^3)	4500	3300	2000	11200	n/a
Mass w/o contingency (kg)	12	3.6	3	20	34
Mass contingency (%)	30				
Mass with contingency (kg)	15.6	4.6	3.9	26	44
Average power w/o contingency (W)	65	6	15	5	10
Average power contingency (%)	40				
Average power with contingency (W)	91	8.4	21	7	14
Mission data volume w/o contingency (Mb)	1476	1.8	252	4190*	n/a
Average data volume contingency (%)	30				
Average data with contingency (Gb)	1.9	0.002	0.3	5447*	n/a
Instrument Fields of View (°)	n/a	n/a	n/a	0.29	n/a

*Instrument average science data rate without contingency in kbps.

3.2 Flight System

The representative spacecraft, designed for the EMF mission study report, and its subsystem mass and power are shown in Figure 4 and Table 5. The spacecraft should be similar to spacecraft used in reference missions. A particular mission will have many design choices for instrument accommodations that will result in adjustments to the spacecraft shown here. We view the representative spacecraft to be conservative on mass and power with multiple launch opportunities and provides many options to further reduce mass and power at low risk.

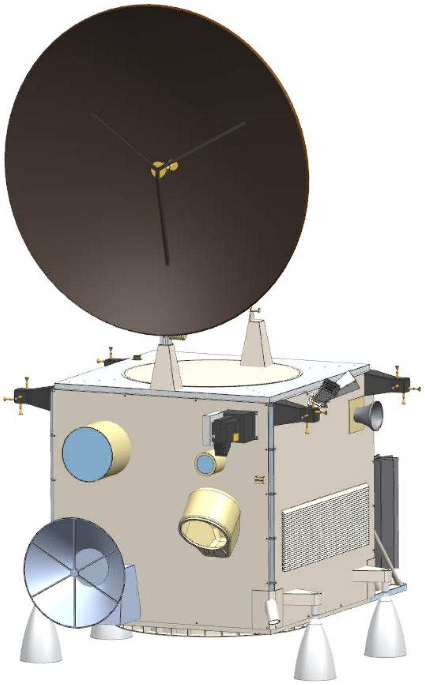

Figure 4. Representative Spacecraft

Table 5. Spacecraft Mass and Power Table

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures & Mechanisms	422.8	20%	507.4	N/A	N/A	N/A
Thermal Control	40.6	20%	48.7	N/A	N/A	N/A
Propulsion (Dry Mass)	161.1	20%	193.3	N/A	N/A	N/A
Attitude Control	21.5	10%	23.6	103.9	10	114.3
Avionics	43.1	10%	47.4	178.0	10	195.8
Telecommunications	22.8	12%	25.5	219.0	30	284.7
Power	183.2	17%	214.3	5.0	10	5.5
Total	895.0	18.5%	1,060.2	**505.9**	**18.7**	**600.3**

Characteristics of the EMF spacecraft are shown in Table 6 below.

Table 6. Flight System Element Characteristics Table

Flight System Element Parameters (as appropriate)	Value/Summary, units
General	
Design Life, months	144
Structure	
Structures material (aluminium, exotic, composite, etc.)	Composite
Number of articulated structures	HGA
Number of deployed structures	HGA
Thermal Control	
Type of thermal control used	Passive, MLI, Heat Pipes, Thermal pump, Louvers
Propulsion	
Estimated delta-V budget, m/s	2,380 m/s
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Regulated bipropellant
Number of thrusters and tanks	16 ACS Thrusters 4 Main Engines 2 MMH Tanks 2 NTO Tanks 2 Pressurant Tanks
Specific impulse of each propulsion mode, seconds	Primary, ME Mode: 315s (299.7s at -3σ) Secondary, ACS Mode: 300s (285s at -3σ)
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial, Nadir, Solar
Attitude control capability, degrees	~< 0.1 degrees
Attitude knowledge limit, degrees	~< 30 arcsec
Agility requirements (maneuvers, scanning, etc.)	DSM
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	HGA
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	CSS: 2π stradian ST: 30 arcsec boresight IMU: ARW = 0.07 deg/root-hour, Bias: 1 deg/hr RCS: 5 lb Wheel: 0.2 Nm, 250 NMS
Avionics (Command & Data Handling)	
Flight Element housekeeping data rate, kbps	~1 kbps
Data storage capacity, Tbits	3.5 Tbits
Maximum storage record rate, Mbps	2 Mbps
Maximum storage playback rate, Mbps	2 Mbps
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Two 16-GPHS STEM-RTGs
Array size, meters x meters	N/A
Solar cell type (Si, GaAs, Multi-junction GaAs, concentrators)	N/A
Expected power generation at Beginning of Life (BOL) and End of Life (EOL), watts	800 (BOL), 580 (EOL)
On-orbit average power consumption, watts	~450
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	15.25

3.3 Concept of Operations and Mission Design

The EMF mission includes a 9-year cruise to Saturn and multiple Enceladus plume flythroughs. Extensive trade studies have been conducted to optimize the feasible launch energy and ΔV while minimizing time-of-flight. One trajectory option (Table 7) launches in Oct 2038 and was selected for its mission design feasibility. Backup launch opportunities were explored. Multiple options using Venus-Earth-Earth gravity assist are available from 2031 through 2039.

During the science phase, EMF is in Saturn orbit and encounters Enceladus approximately every month at a speed $\leq$ 4 km/s. During each encounter EMF flies through the plume. Because of Enceladus' small size and low gravity, the EMF ground track can be moved transverse to the nominal track of any flythrough. EMF follows the proven *Cassini* approach for estimating spacecraft, planet, satellite, and measurement parameters (e.g., Doppler range, OpNav data, small body forces, thruster firings, thermal radiation pressure from RTG and Saturnian system gravitational and orbital parameters). *Cassini* achieved better orbital determinations and delivery than EMF requires (Pelletier et al., 2012; Antreasian et al., 2008). The RF communications subsystem provides Ka-band communications throughout all phases of the mission.

Table 7. Mission Design

Parameter	Value	Units
Mission Lifetime	144	mos
Launch Site	Cape Canaveral	
Total Flight Element #1Spacecraft Mass **with** contingency (includes instruments)	1,240.0	kg
Total Flight Element #2 Mass **with** contingency (includes instruments)		kg
Propellant contingency	10	%
Propellant Mass **with** contingency	2,500.4	kg
Launch Adapter Mass **with** contingency	71.0	kg
Total Launch Mass	3,811.4	kg
Launch Vehicle	Falcon heavy Expendable	Type
Launch Vehicle Lift Capability	5,000	kg
Launch Vehicle Mass Margin	1,188.6	kg
Launch Vehicle Mass Margin (%)	31	%

The operations and data systems information in Table 8 is representative of EMF mission designs. The table provides representative communication parameters for the launch and cruise phase and the final science orbit. A particular mission will make minor alterations to some of the parameters.

Table 8 Representative Mission Operations and Ground Data Systems Summary

Communications	Launch and Cruise	Science Orbit
Number of Contacts	1 per month	1 per day
Number of Weeks for Mission Phase, weeks	432	190
Downlink Frequency Band, GHz	32	32
Telemetry Data Rate(s), kbps	HGA > 77.5 MGA > 0.021 LGA > 0.0007	HGA > 77.5 MGA > 0.021 LGA > 0.0007
Transmitting Antenna Type(s) and Gain(s), DBi	HGA 58.67 MGA 22 LGAs 7.4	HGA 58.67 MGA 22 LGAs 7.4
Transmitter peak power, Watts	200	200
Downlink Receiving Antenna Gain, DBi	79	79
Transmitting Power Amplifier Output, Watts	100	100
Total Daily Data Volume, (MB/day)	>139.5	>139.5
Uplink Information		
Number of Uplinks per Day	1	1
Uplink Frequency Band, GHz	34.45	34.45
Telecommand Data Rate, kbps	HGA > 137 MGA > 0.613 LGA > 0.036	HGA > 137 MGA > 0.613 LGA > 0.036
Receiving Antenna Type(s) and Gain(s), DBi	HGA 58.67 MGA 22 LGAs 7.4	HGA 58.67 MGA 22 LGAs 7.4

4.0 Risk List

The top EMF mission concept risks have been identified with likelihood (L) and consequence (C) levels, and with associated mitigation strategies and are summarized in a risk matrix (**Figure 5**).

1. **Long mission duration (degradation, failure) (L=1; C=4)**. Given the planned mission duration, including the time required to reach Enceladus, then there is the possibility mission degradation or failure could occur. Possible mitigation strategies include: (1) leverage experience form prior missions; (2) conduct rigorous reliability analyses to inform decision making; (3) include redundancy in mission-critical flight system elements.
2. **MMRTG or 16-GPHS STEM-RTGs availability and spacecraft integration (L=2; C=3)**. Given the thermal and electrical uncertainties, behavior of MMRTGs and16-GPHS STEM-RTGs, and the extensive activities required for NEPA approval, then there is a possibility the spacecraft will require a late redesign, resulting in a cost and

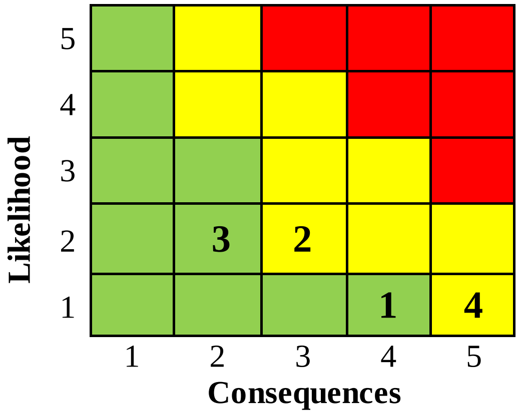

Figure 5. 5x5 risk chart to assess the likelihood and impact of top risks identified for the EMF mission concept.

schedule impact. Possible mitigation strategies include: (1) Work proactively with NASA and DOE on the current issues with MSL MMRTG shorts and spacecraft interfaces; (2) conduct early analyses to ensure MMRTG compatibility with spacecraft and launch activities; (3) leverage experience form prior missions and early NEPA start.

3. **Impact of contamination control on cost and schedule (L=2; C=2)**. Given the mission's contamination control requirements, then there is the possibility that as the design matures, the results of ongoing analyses will indicate the need for unplanned activities, resulting in cost and schedule impacts. Possible mitigation strategies include: (1) prioritize contamination control analyses, particularly in the early phases; (2) develop detailed contamination control plans and protocols to address requirements with margin; (3) implement new contamination control strategies as described elsewhere (McKay et al., 2020).
4. **Saturn Orit Insertion (critical event) (L=1; C=5).** Given that SOI represents a critical event during cruise to Enceladus, then there is the possibility mission success requirements may not be met. Possible mitigation strategies include: (1) leverage experience form prior missions; (2) Analyze lessons learned from insertions (e.g., defer fault responses until after burn, as on *Messenger*); (3) design, build, and test critical-event scripts early; perform rehearsals and simulations using proven critical-event processes; (4) define critical events and timelines during Phases A and B; (5) develop plans and contingency plans leading to each critical event.

5.0 Development Schedule and Schedule Constraints

5.1 High-Level Mission Schedule

The mission schedule is similar to reference missions and is typical of a number of New Frontiers schedules. Further refinement may result in changes in some of the segments and in schedule reserve.

Table 9. Key Phase Duration

Project Phase	Duration (Months)
Phase A – Conceptual Design	9
Phase B – Preliminary Design	14
Phase C – Detailed Design	18
Phase D – Integration & Test	28
Phase E – Primary Mission Operations	144
Phase F – Extended Mission Operations	0
Start of Phase B to PDR	10
Start of Phase B to CDR	27
TOTAL Development time Phase B-D	60
Project Total Funded Schedule Reserve	4

5.2 Technology Development Plan

The EMF mission concept as defined here assumes technology development for aspects of the science payload. A TRL roadmap for the SHS is given (Table 10). Thermal challenges associated with handling a small sample volume must also be addressed. The TRL maturation plan leverages COLDTech funding to finalize the sample chamber designs and conduct thermal/vacuum testing.

Table 10. Roadmap for SHS technology development.

Stage	Technology Development	Off Ramp
Sample Handling System (SHS)		
TRL 5→6: System meets all requirements for automated operation and is demonstrated on ground.	Technical requirements: performance of critical components are proven in flight-like environments (thermal, vibration, shock, radiation); interfaces developed and tested in flight-like environments (thermal, vibration, shock, radiation).	Before PDR
TRL 6→8: Flight qualification	Demonstration against all flight-ready parameters	Pre-ship review

6.0 Mission Life-Cycle Cost

6.1 Costing Methodology and Basis of Estimate

The Phase A-D cost of an EMF mission concept detailed point design was previously estimated to be less than $850M (FY15) with 30% reserve. This cost was done via a combination of grassroots, Price H and other parametric tools as well as independent total cost checks. The cost was reviewed extensively by multiple internal and external reviewers. This is approximately $973 M with 30% reserve in FY25 dollars, comfortably within the target New Frontiers cost in the decadal study guidelines with enough margin for some errors or growth or the application of 50% reserves applied to lower maturity mission studies (~$1.1B FY 25).

Appendix A: Acronyms

CBE	Current Best Estimate
CDA	Cosmic Dust Analyzer
CHNOPS	Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorous, Sulphur
CML	Concept Maturity Level
COLDTech	Concepts for Ocean worlds Life Detection Technology
DOE	Department of Energy
EMF	Enceladus Multiple Flybys
EOD	Electrochemical Organic Detector
ESA	Electrochemical Sensor Array
FY	Fiscal Year
HRMS	High-Resolution Mass Spectrometer
ICA	Inorganic Chemical Analyzer
ICEE	Instrument Concepts for the Exploration of Europa
INMS	Ion and Neutral Mass Spectrometer
LORRI	Long Range Reconnaissance Imager
MATISSE	Maturation of Instruments for Solar System Exploration
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MEV	Maximum Expected Value
MSL	Mars Science Laboratory
NASEM	National Academies of Sciences Engineering and Medicine
NAC	Narrow Angle Camera
NEPA	National Environmental Policy Act
NF	New Frontiers
OCA	Organic Chemical Analyzer
PICASSO	Planetary Instrument Concepts for the Advancement of Solar System Observations
R&A&D	Research and Analysis and Development
RF	Radio Frequency
ROW	Roadmap to Ocean Worlds

RTG	Radioisotope Thermoelectric Generator
SC	Spectral Camera
SHS	Sample Handling System
SMS	Separation Mass Spectrometer
SOI	Saturn Orbit Insertion
SPT	South Polar Terrain
STM	Science Traceability Matrix
TRL	Technology Readiness Level
UV	Ultra-Violet
WCL	Wet Chemistry Laboratory

Appendix B: Citations

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