A General STM for the Enceladus Vent Explorer Mission Concept and a Case for Vent Exploration. J.M. Weber,[1] L.E. Rodriguez,[1,2] M. Ono,[1] M. Cable,[1] M. Chodas[1] and M. Ingham[1], [1]NASA Jet Propulsion Laboratory, California Institute of Technology [2]Lunar and Planetary Institute

Introduction: Enceladus has been of great interest to the scientific community since the discovery of the plume and organics within it during the Cassini mission [1-3]. With the Planetary Science and Astrobiology Decadal Survey 2023-2032 prioritizing Orbilander as well as including Enceladus as a destination for upcoming New Frontiers (NF) calls [4], Enceladus is recognized as a key target for future missions. In order to understand the relevant science questions for Enceladus, a series of workshops was held at NASA JPL, including scientists, technologists, and engineers with different backgrounds. From these workshops, a general science traceability matrix (STM) was generated. This STM was not based on any specific mission architecture and was designed to capture all of the scientific interests of the workshop attendees regardless of flight readiness. The STM suggests that a combination of multiple mission types are necessary to cover the entire spectrum of compelling Enceladus science. In particular, a mission to enter and explore an active vent is critical for achieving some of the high-priority goals.

Science Motivation: The STM was motivated by two science goals called out in the 2013-2023 Planetary Science Decadal Survey [5]. While these were based off the previous Decadal Survey, we think these still align well with the goals of the new Decadal Survey [4]. The first goal in the STM was to determine the origin and evolution of Enceladus, including exchange of materials between the surface and subsurface. This Science Goal 1 was split into three objectives:

(1.a) Determine the formation of Enceladus in relation to: The Saturn subnebula, the moon debris, and he current ring system,

(1.b) Constrain the age of Enceladus, and

(1.c) Identify the thermal evolution Enceladus has undergone in its history, including the degree of surface/subsurface exchange of materials.

The second overarching science goal in our STM is focused on astrobiology/habitability and aims to determine whether organic synthesis continues today on Enceladus and whether this supports an extant biosphere. For Science Goal 2 (there are two objectives:

(2.a) Determine how long habitable conditions have persisted on Enceladus, and

(2.b) Determine if there is life on Enceladus presently, and evaluate if Enceladus only hosts abiotic/prebiotic chemical reactions vs if there is biotic material present.

From this high-level decomposition, objectives and specific instrument options were then selected for each architecture class. As this was a general STM, many instruments of interest were identified to address the science goals.

Mission Architecture Type	Instrument	STM Goal / Objective
Orbiter/flyby	Camera, IR, magnetometer, NAC/WAC, thermal imager, Limb observations, gravity science, LIDAR, SHS, Radar	Science Goal 1 (1a, 1b)
Plume flythroughs	MS, UV-Vis, IC, IR, LIBS, Raman, microfluidic systems, SHS, TLS, Dust analyzer, plasma spectrometer	Science Goal 1 (1a, 1b) Science Goal 2 (2b)
E-ring analysis	MS, SHS, TLS, IR	Science Goal 1 (1a)
Surface / Landed	Raman, Camera, LIBS, magnetometer, MS, microfluidics, seismometer, SHS, temperature probe, hydrometer, XRD, LIBS, Raman, IR, UV-Vis, IMS, plasma spectrometer, conductivity probe	Science Goal 1 (1a, 1b, 1c) Science Goal 2 (2b)
In the Vent	Raman, LIBS, Sounding Radar, MS, seismometer, camera	Science Goal 1 (1b, 1c) Science Goal 2 (2a)
Direct Ocean Access	Fluorometer, microscopy, DHM, MS, Raman, LIF, nanopore systems, IMS, GC/LC, UV-Vis, HRMS, IC, LIBS, SHS, magnetometer, microfluidic systems, camera, seismometer, heat flow/temperature probes, hydrophone, sonar, conductivity probe	Science Goal 1 (1b, 1c) 2 Science Goal 2 (2a, 2b)
Sample collection	Both spaceflight instruments (i.e., MS, LIBS, LIF, TLS, camera, UV-Vis) + further analysis when returned	Both science goals, dependent on samples collected

Table 1. Instruments identified in the STM organized by mission architecture and science objective.

Instrument Class	Purpose	General Considerations
Organic detection (e.g., MS, IMS, Raman, SHS)	Determine presence / ratio of organic materials or biomaterials, homochirality; isotopic ratios	Would need to differentiate organic molecules (i.e., high resolution, parallel lines of evidence). Dependent on concentration
Microscopic Detection (e.g., DHM, microscopy)	Look for non-Brownian motion; cell like structures; complex structures	These instruments only explore a small area, sample choice is especially important. Dependent on cell concentrations
Macroscopic Detection (e.g., Camera)	Identify large structures; search for multicellular life / biosignatures	Requires repeated analysis of samples to avoid false positives. Still limited in area of imaging
Habitability context (e.g., IR, temperature probe, seismometer)	To understand the surrounding geologic setting; validate control test	While not directly looking for life, validating the reasonableness of the conditions is important

Table 2. General instrument types used in life detection based on the science goals identified.

Instrument Selection: These instruments were organized by mission architecture type, and the science objectives they can address (Table 1). The instruments are redundant across multiple investigation types, allowing for options as the science goals are down-selected for individual missions. However, it is important to note the operating requirements of the instruments, including distance from targeted material and sample volume required. In addition, the flight readiness of these instruments varied greatly, which can be used to inform technology development.

Life detection is an important aspect of the STM and developing instrument suites for life detection would benefit from redundancy, the ability to repeat samples, and integrated sample handling. Development of such systems is beneficial for life detection (Table 2).

Lessons Learned: Based on the science questions and instruments raised, there was significant interest within the workshop on accessing ocean materials directly. While plume flythroughs and collection of plume material on the surface would allow for significant science gain, accessing the vent and ultimately the ocean would allow for better understanding of gradients and chemical species within the ocean, which is critical for accomplishing Science Goal 2. This would also provide unaltered samples of the ocean, as surface and orbiting missions would only access what is ejected from the plume. Ocean access would allow for larger sample volumes, enabling life detection techniques. Existing studies suggest that a robotic mission into Enceladus vent for in-situ measurements and/or sampling would be technically feasible [6] and implementable as a Flagship-class mission [7].

Conclusions and Future Directions: We have developed a novel STM for Enceladus science. More instruments were identified than would be needed to address the science questions; there are a variety of combination of instruments that address the key science questions. This was done intentionally to build flexibility into the STM. Based on the science questions and instruments identified, accessing direct ocean samples is of significant interest to the science community. Technology development to access the vents of Enceladus and subsequently the subsurface ocean are imperative to achieving the goals.

References:

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