Vertical Entry Robot for Navigating Europa (VERNE): Mission Concept and System Design

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Several moons in our solar system, including Europa, are believed to host large bodies of liquid water beneath ice shells. These water bodies are compelling locations in the search for life beyond Earth, but present significant challenges to access in future planetary missions. The Vertical Entry Robot for Navigating Europa (VERNE) is a robotic mission concept to penetrate and operate within Europa's ice shell and ocean funded through the Scientific Exploration Subsurface Access Mechanism for Europa (SESAME) program. SESAME requires a vehicle capable of penetrating a hypothetical 15 km Europan ice shell within three years. VERNE will utilize a thermo-mechanical drill to descend into the ice while a suite of onboard sensors constrains ice properties and look for life by analyzing the meltwater. Data will be relayed to a surface lander via a redundant communication system comprised of a primary optical fiber cable and secondary wireless acoustic repeaters. Upon nearing the base of the ice shell, VERNE will release an anchor and then breakthrough into the ocean to profile the upper 100 m of the ocean and ice interface, a region with high potential for evidence of life. Here we present the mission success criteria, concept of operation, and vehicle architecture. We identify key technologies that are currently available as well as those that require maturation to support future subsurface access of ocean worlds. Throughout this activity, the design team sought to leverage experience with analog environments on Earth to generate a concept which demonstrates that such a mission is feasible within the coming decades.

I. Nomenclature

COMCDH	=	Communications, Command, and Data Handling
EPS	=	Electrical Power Systems
GNC	=	Guidance, Navigation, and Control
RTG	=	Radioisotope Thermal Generator
SCIPAY	=	Science and Payload
SESAME	=	Scientific Exploration Subsurface Access Mechanism for Europa
SHS	=	Sample Handling System
STR	=	Structures
THE	=	Thermal Systems
TRL	=	Technology Readiness Level

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II. Introduction

The Vertical Entry Robot for Navigating Europa (VERNE) project is a mission concept for the exploration of Europa's ice shell and subsurface ocean as a part of NASA's search for life. Europa is a moon of Jupiter that most likely contains a stable, saline, liquid water ocean covered by an ice shell 10-30 km thick [1, 2]. This liquid water ocean, coupled with evidence of a geologically active interior [3, 4], suggests that Europa may contain both the raw ingredients and geochemical cycles required to evolve and support life [5–7]. Supported by the NASA's Scientific Exploration Subsurface Access Mechanism for Europa (SESAME) program, VERNE was one of five studies to evaluate mission elements or full mission designs which could be conducted as early as the 2030's. A central element of the study is therefore to assess the technology readiness level (TRL) of critical system components to provide a recommendation for key research and development needed to enable mission success in the coming decades.

The SESAME program provides VERNE with minimum constraints for a three-year sub-surface mission to an ocean beneath a 15 km ice shell. It is assumed that a spacecraft will carry VERNE to Europa in the coming decades, and a separate lander will deliver it to a desired location in contact with the surface. Power sources are constrained to be Radioisotope Thermoelectric Generators (RTG) or a nuclear power system, and mass is to be minimized; the subsurface vehicle mass limit is 200 kg, excluding science payload and power source. The scientific goals of the proposed design are to: 1) characterize the physical and compositional properties of the Europan ice shell and ocean, and 2) to search for signs of life, or biosignatures. The design study presented here seeks to enable the most ambitious science possible within these constraints and identify important areas for future development needed to facilitate a such a mission.

Mission Study Organization

The VERNE study has been broken into two phases. Phase I (year 1) focused on developing the full conceptual mission study needed to identify the key technologies required to perform such a mission and identification of technological gaps; this paper primarily addresses that phase. Phase II selects key technologies from Phase I and seeks to improve their TRLs through prototyping and testing in laboratory and analog environments. Phase II is currently underway.

In Phase I, the team was organized into the following vehicle subsystems:

1) **Sample Handling System (SHS)** - water sample handling and processing
2) **Science and Payload (SCIPAY) -** investigates the environmental conditions and has compiled the suite of representative life-detection instruments **- model payload consideration**
3) **Structures (STR)** – vehicle structure and mass budget,
4) **Communications, Command and Data Handling (COMCDH)** - data transmission through ice shell,
5) **Guidance, Navigation, and Control (GNC)** - vehicle navigation and control, including hybrid thermal/mechanical drill,
6) **Electrical Power Systems (EPS)** - power generation, distribution, and budget, and
7) **Thermal Systems (THE)** - thermal management for the vehicle, drill, and instrumentation.

III. Science Motivation for a Europa Mission

The Voyager and Galileo missions revealed the surface of Europa to be dominated by water ice and geologically young – a mere 40-60 million years old [8]. A key discovery of the Galileo mission was that an ∼100 km thick salty liquid water ocean may lie beneath the outer ice shell [1. 2]. Since then, Europa's subsurface ocean has remained a subject of high scientific interest because it may hold conditions favorable for life [9–12]. Fortunately, NASA's upcoming flyby mission, Europa Clipper [13], with a potential Europa Lander mission to follow [14], aim to address whether conditions at Europa are conducive for life by searching for subsurface pockets of brine, placing better constraints on the ice shell thickness [13], and determining the composition of the icy crust [14]. Due to Europa's surface conditions, however, these missions may not directly detect signs of extant or past life; for example, Jupiter's magnetosphere constantly bombards Europa's surface with highly energetic particles that are likely to chemically and physically alter or destroy organic molecules [15-17]. Since life as we know it requires liquid water, and given the harsh surface conditions, the best way to assess if Europa is or was inhabited is likely to investigate its liquid water reservoirs.

While Europa's subsurface ocean may prove difficult to reach through an ∼10–30 km thick ice shell, it has the highest science potential and possibility of supporting life. Similar to Earth, Europa's ocean sits on top of a silicate

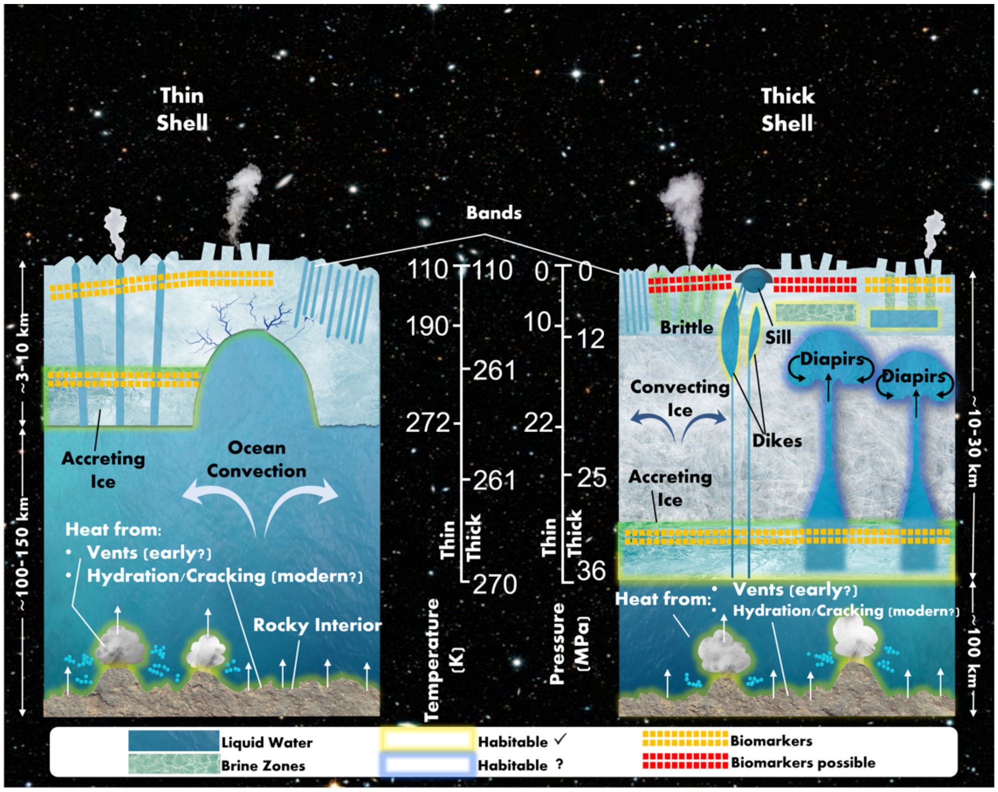

Fig. 1 Cartoon showing the two prevailing ice thickness estimates of the Europan ice shell and hypothesized dynamic transport processes that create chemical cycles that could make Europa habitable (adapted from [22])

mantle which allows water-rock reactions, such as serpentinization, to provide both abiogenic hydrogen and heat into the ocean [17]. Furthermore, heat in the silicate mantle (generated by Jupiter's tides) may provide enough heat to cause hydrothermal venting at Europa's sea floor, providing chemical and thermal gradients for life to thrive as it does on Earth [19, 20]. As Europa's surface appears geologically young, nutrients at or near the surface may also be delivered to the ice shell interior, and potentially the ocean, through cycling of the crust via geologic processes [20], such as a potential plate tectonic-like subduction of the icy crust [21] or saline water pockets within the shell [22] ("sill" in Fig. 1). Such reservoirs may be relatively large (>10 km diameter) and~1-5 km below the surface in the shell [23, 24] and may be easier to reach than the ocean. Both the ocean and shallow liquid water have high potential relevance for Europa's habitability because of the available water and potential physical and chemical gradients that can be utilized as energy sources for microbial life. For example, the ice-ocean interface of Earth's polar regions are teeming with microbial life [24], where they are provided chemical gradients which similarly may occur both at the ice shell-ocean boundary. Determining whether these regions are potentially conducive for life, or the environmental context, is an essential input for differentiating abiotic and biotic interpretations. The Mars Viking II life-detection experiment may prove a cautionary tale in this respect: initial results from the Labeled Release experiment suggested the presence of life, but the later identification of widespread perchlorates that likely destroy organic compounds makes this result suspect [25]. Thus, VERNE's goal is to reach one of these water bodies to detect signs of extinct or extant life while characterizing the environment of the ice shell and water body.

Relevant Measurements and a Representative Payload

To measure the composition of and search for signs of life in the Europan ice shell and ocean, VERNE must sample representative portions of the ice. For a melt probe, the simplest way to achieve this objective is to sample the melt pocket surrounding the vehicle at discrete points in the shell, giving many opportunities to gain context about the geophysical history and environment of Europa's ice shell. Each sample will provide a small portion of the melt water surrounding the vehicle and will be delivered to the different instruments on the payload. In order to maximize the potential science return, the VERNE study established a model payload of instruments that have the ability to make a wide range of measurements, as described in Table 1, during the descent and in profiling the subsurface water body. The planning payload represents one possible suite of instruments for future flight that has both the ability to characterize the surrounding environment through quantifying metrics such as temperature and salinity, and identify macromolecules of life including DNA, lipids, and proteins. Identifying concentrations of salts and other materials will help give environmental context by determining ionic composition and concentration and other inorganic species that are available for metabolic processes for macromolecule production. Temperature, depth, and pressure will be measured to give more contextual and dynamic information on the shell and ocean. Organic molecular species will be identified to understand the availability of more complex molecules that can be instrumental to life such as the smaller complex organics like amino acids, which are the building blocks of protein, and larger complex organics and informational polymers like DNA.

More than 30 instruments and techniques were surveyed that could be useful for this type of mission. Key documents such as the Roadmap to Ocean Worlds, the Europa Lander Study 2016 Report [26], and the Ladder of Life Detection [27] helped guide the down-selection process. The instruments were chosen to create a cohesive payload that is best equipped to overlap in data acquisition for the overarching life detection goal, as shown in Table 1, while preserving a flexible sample handling approach in order to not eliminate other instrumentation and measurement techniques from future selection. Although this planning payload is not the final suite for a Europan probe mission, it can be used to inform other systems of the anticipated power, volume and data requirements of a science payload, as well as inform the type of samples that may be needed by the future instrument suite.

Table 1 Description of VERNE's model payload, measurement capabilities, example instruments for the payload and their states of development, and traceability to the existing Ladder of Life Detection (LoLD). [1]Estimated TRL for flight. A maximum TRL (6) is assessed for operational systems tested for Earth applications. [2]Numerical representation of relevant LoLD "rung" (Table 2 in [27]): 0 - Habitability, 1 - Biofabrics, 2 - Potential metabolic byproducts, 3 - Potential biomolecule components, 4 - Molecules & Structures Conferring Function, 5 - Metabolism, 6 - Growth & Reproduction, 7 - Darwinian Evolution. '()' indicates partial relevance under certain conditions

Science Goal	Instrument	Science Objective	Example System (TRL[1])	LoLD[2]
Life Detection	Mass Spectrometer	Life-relevant organic molecules	OCEANS [28] (3-4)	0,2-5
	Microscope	Cell morphology and motility	SHAMU [29] (3-(6))	1,6
	Sequencer	Sequence DNA/RNA of potential Europan life	SETG [30] (4)	3,4
Environmental Context	ISE	Ionic species	MICA [31] (3-4)	0,5
	Raman	Inorganic and organic composition	InVADER [32] (4-5)	0,2
	CTD	Ocean/water physical properties	SBE 41/41CP [33] (6)	0

As can be seen in Table 1, the VERNE science payload contains instrumentation that has the ability to detect a wide range of indicators for life and contains compatible instruments that have the ability to provide data that builds upon each other, thus increasing potential science return for the proposed instrument suite. The current planning payload for VERNE consists of the following instruments: solid contact ion-selective electrodes (ISEs); conductivity, temperature, and pressure/depth (CTD) sensor; Raman spectrometer; microscope; mass spectrometer; and informational polymer sequencer. As VERNE descends through the ice shell measurements will provide context on the environment and how it is changing, provided by the ISEs, CTD, and Raman spectrometer that work on flow-through samples. The ISE's will measure the concentration of specific ions in the sample, which will help determine what types of salts are present throughout the ice shell. The CTD will measure salinity and the temperature as a function of depth; this can be used to better understand the habitability of the ice shell, subsurface liquids, and the dynamics of the ocean. The Raman spectrometer will gather compositional information in the ice shell and will identify inorganics and organics that may help to inform sampling cadence of discrete sampling. The instruments that support identifying life are the microscope, mass spectrometer, and informational polymer sequencer. The microscope will be used to identify cell-like structures and particle morphologies within water samples, as well as detect active motility. After the sample is processed and imaged, it will be sent to the mass spectrometer and informational polymer sequencer. The mass spectrometer will be used to detect sample chemical composition including organics. The informational polymer sequencer will identify the order of subunits of DNA/RNA or other macromolecules indicative of life.

IV. Mission Concept and Baseline Requirements

The SESAME program call requested teams to design a vehicle capable of penetrating 15 km of ice in at most 3 years, and with system mass less than 200 kg (excluding power source and science payload), with other mission details left to the study team. To maximize the scientific value of the mission, scientific sampling requirements were built into the mission success criteria, specifying at least one set of samples for every kilometer of ice to characterize the ice environment, and one set at an ice-water interface (either at a water pocket or the sub-surface ocean), where evidence of life is most likely to exist. To narrow the design space to higher TRL concepts that could fly within the next two decades, the vehicle's main power source was constrained to RTGs. The minimum Mission Success Criteria, shown in Table 2, were developed by the VERNE team to accomplish the scientific objectives of the mission, while full mission success is defined by a higher frequency of scientific data collection and transmission.

Table 2 VERNE Mission Success Criteria, which follow from the SESAME call and science objectives

Pass/Fail Criteria	Minimum Mission Success	Full Mission Success
Dig into the Europa Ice Shell		
Reach a subsurface water body **-or**	X	X
Reach 15 km into the subsurface in three years	X	X
Conduct analysis of the composition of the ice shell and water body		
Analyze single sample of liquid melt-water per kilometer travelled	X	X
Analyze triplicate sample of liquid melt-water per 250 meters travelled		X
Analyze triplicate sample of liquid water from ocean/reservoir	X	X
Profile 50 m of the ice/water interface for 3 Laplace resonances (10 day orbital cycle around Jupiter)		X
Conduct analysis of the structure of the ice shell and water body		X
Communicate with Lander		
Return Payload and Telemetry data to Lander	X	X
Transmit all relevant on-board data		X
Vehicle Constraints		
Shall not exceed 200 kg in mass (excluding Power Source and Science Instruments)	X	X
RTGs shall be used as the main power source of the vehicle	X	X

Concept of Operations

The vehicle design and mission profile were developed to ensure that the mission satisfies its science objectives. A single penetrating robot that houses the science payload along with the necessary spacecraft systems was agreed upon by the team as the best approach to conduct such a unique mission. A monolithic vehicle was found to have the highest feasibility and lowest mission risk, compared to an alternative architecture of a separate vehicle for water operations. The mission profile, visualized in Fig. 2, and detailed by operation mode in Table 3, is specified as follows: VERNE embeds itself into the ice surface upon delivery by the lander vehicle and enters Start of Mission Mode. The deployed vehicle will then drill through the ice shell using a hybrid thermal/mechanical drill in Travel Mode. During the descent, VERNE will collect and analyze melt-water samples at regular intervals in Science (Ice Shell) Mode. Vehicle and payload data will be transmitted via optical fiber cable to the lander with wireless relays as backup in Communication Mode. If an obstacle is encountered while traveling through the ice shell, VERNE will enter Obstacle

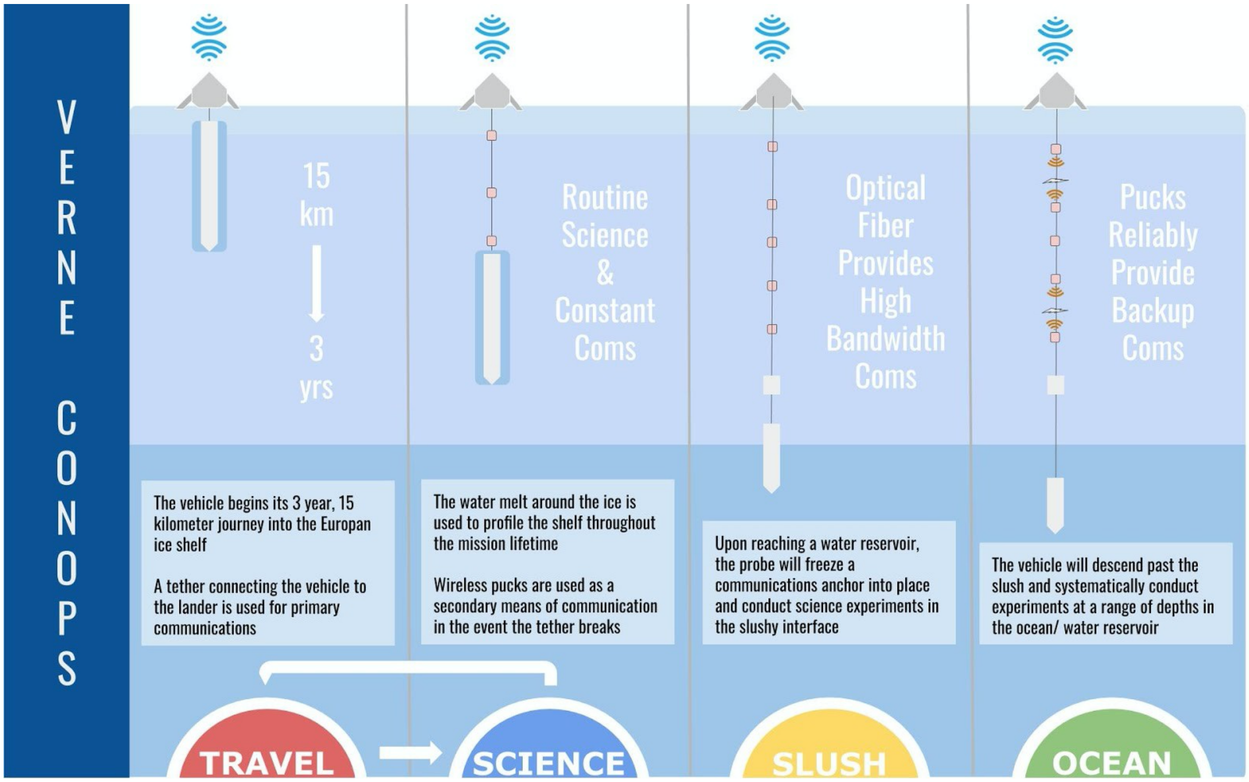

Fig. 2 VERNE Concept of Operations. The operations begin after VERNE has been delivered to Europa's surface. The vehicle will descend through the ice shell, sampling and analyzing water from its surrounding melted water pocket. Communication with a surface lander will be completed using a fiber optic tether with acoustic repeaters for redundancy. Upon reaching a water reservoir or ocean, the vehicle will deploy an anchor that allows the body of the vehicle to descend into the ocean and conduct hydrographic profiles and sampling.

Avoidance Mode for small objects or Obstacle Impact Mode for unavoidable objects such as salt layers [34,35]. The sampling and analysis of the subsurface body of water, particularly through the completion of "up-down" profiles within the body of water, is a unique mission element with heritage from how ice and ocean dynamics are studied on Earth. This requirement introduces a unique set of operations. When VERNE encounters the ice-water interface, either at the ocean or a water reservoir within the ice shell, the vehicle will enter Anchoring Mode and release an anchor that will lock the rear section of the vehicle into the ice. The remaining profiler section will stay connected by cable and perform controlled ascent and descent in Water Body Profiling Mode using a winch located on the profiler. The vehicle will first take multiple samples at the interface, as this location has high potential for harboring signs of life on Europa, then conduct multiple profiles in the water body to measure the properties of the water column as well as search for evidence of life, continuing until mission End of Life.

Table 3 VERNE Concept of Operations by Mode

Operational Mode	Description	Concentration of Power
Start of Mission	VERNE is on the surface of Europa, drill is in contact with surface. Mechanical drilling will be the focus due to the hardness of cryogenic ice.	GNC/Drilling, THE
Travel: 0-15km	VERNE melts and mechanically drills into ice while maintaining obstacle detection sensing. Tether is spooled behind vehicle, and provides telemetry to the lander. Payload may analyze samples under low power.	GNC/Drilling, COMCDH

Science (Ice Shell)	VERNE takes in and analyzes water samples using its payload. Power systems enables nominal instrument operations, COMCDH manages large data packets.	SCIPAY, SHS, COMCDH
Communication and Data Handling	COMCDH transmits data to lander via fiber-optic tether, or using acoustic repeaters across breaks in tether.	COMCDH, GNC
Obstacle Avoidance	GNC adjusts vehicle attitude around obstacles, COMCDH transmits telemetry to lander; other systems are relegated to low-power to preserve obstacle avoidance capabilities.	GNC, COMCDH
Obstacle Impact	Mechanical drilling is prioritized to allow vehicle to pass through obstacles it cannot avoid.	Drilling/GNC
Anchoring	Ahead of a target for profiling, a section of the vehicle containing the anchor is separated, and the anchor is deployed to remain in the ice as the rest of the vehicle continues its descent using the profiling tether management system (TMS).	Anchoring (STR), Profiling (STR)
Water Body Profiling	Vehicle takes in samples at the ice-water interface. If ocean current can be determined, and is safe to proceed with profiling, vehicle descends with its TMS to collect a profile up to 100m in the ocean.	Profiling (STR), SHS, SCIPAY, COMCDH
End of Life	If VERNE is in the ocean, operators may choose to cut the tether and communicate to the anchor using the acoustic repeaters until out of range. During this descent, the vehicle will continue to analyze water samples.	COMCDH, SCIPAY, SHS

V. Sample Handling System (SHS)

A. Subsystem Requirements

The sample handling system requirements were developed to support the mission success criteria and fulfill science goals. Moreover, operational flexibility has been a major focus of the system development. The science package described here is a model payload under ongoing development. While still evolving, the proposed instruments can be used to guide the design in terms of size, sample volume, and processing capabilities. To support scientific analysis throughout the ice shell, the sample handling system should be capable of providing continuous flow of unprocessed water to several instruments, such as the CTD and ISE sensors, although flow may be paused to allow equilibration. The sample handling system should also be capable of delivering triplicate discrete samples to the science payload at increments of at least 250 m throughout the ice shell, and at shorter intervals during the ocean profile. Specific sample processing capabilities needed for the full suite of instruments to collect measurements including sample concentration, pressure compensation, and desalination. The total sample volume of all discrete sample instruments (mass spectrometer, Nanopore sequencer) was taken to be on the order of 100s of micro-liters. Finally, the entire sampling system must fit within the vehicle planning payload constraints.

B. Sample Handling System Design

1. Flow Diagram and Components

A flow diagram of a potential architecture for combined flow through and discrete sampling is shown in Fig. 3Fig. 3. The payload is broadly separated into 1) non-destructive ‘front end’ instruments (SC-ISEs, Raman, microscopy) tolerant to high ion concentrations and 2) ‘back end’ instrumentation (separation mass spectrometry and information polymer sequencing) not tolerant of the salts predicted in Europa’s shell [34]. De-salting the sample is likely to be destructive to cell-like morphologies, so this is performed after context-dependent Raman and microscope measurements. To avoid blockages from clogged filters multiple inlet ports are used, opening flow through only one port per sample. Each inlet port will contain a course and fine set of filters to remove other particles that might clog the pumps or processing system. A multi-port valve, also known as a rotary valve, then selects the desired inlet port to collect millifluidic volumes of water and routes it to the instrument path. The samples will first be analyzed by the instruments operating on the unprocessed moving water at ambient pressure, the CTD and ISE sensors. A subset of water can then be sent to a Raman spectrometer and microscope. Alternatively, excess sample water is evacuated from the vehicle, or filtered and retained in a hold that can be used to flush the system and filters backwards in the case of clogging.

Following non-destructive measurements, water goes through a sample processing stage to regulate pressure and remove salts. After a sample has been processed, it will be split between a mass-spectrometer/liquid chromatography and nanopore sequencer, while any solution that is not retentate from the sample processing is evacuated from the vehicle. Products from the instruments or sample processing that arise from chemical altering and cannot be released into the environment will be directed to a containment unit onboard to protect the environment for the duration of the mission.

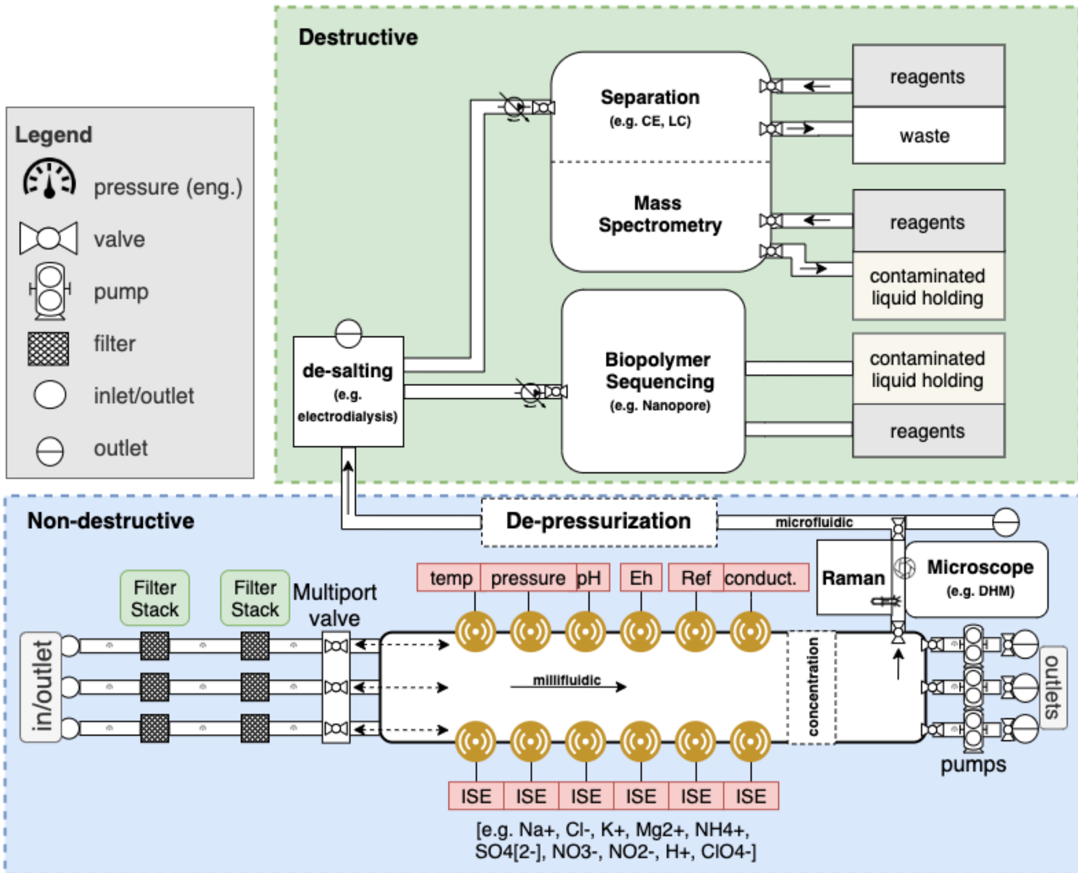

Fig. 3 Flow diagram of proposed VERNE SHS. Important components are noted, including locations of pumps and valves, and the representative suite of instruments. In blue, the path of samples at ambient pressure (and flowthrough sensors) are shown. In green, the path of the samples that will require additional sample processing, such as desalination or de-pressurization.

2. Sample Processing

Several methods for desalting the samples were considered, including electrodialysis (ED), reverse osmosis (RO) and ion exchange resins. Electrodialysis was determined to have the most potential for use on VERNE as it does not filter out dissolved organic matter [36], and can also be coupled with reverse osmosis to concentrate the sample. It has been proven on sample volumes of 0.5-10 mL [37], but further development and evaluation at this sub-milliliter volume is needed. After desalting samples, concentration may be required, for which RO, tangential flow filtration, and concentrating pipettes were considered. RO and concentrating pipettes hold the most potential for the VERNE system, as RO is often paired with ED. Concentrating pipettes do not require a membrane or buffer, and have been proven with micro- or milli-fluidic systems [38].

Upon entering the subsurface ocean, the external pressure is expected to be as much as 20 MPa underneath a 15 km ice shell – although a thicker shell could double this pressure. Operation in this high-pressure environment can be accomplished using a pressure housing and making observations through a view port. Alternatively, the water can be depressurized before delivering it directly to an instrument inside a pressure housing [39]. The latter method has been used with the MBARI Deep Environmental Sample Processor (ESP); water at pressure is pumped into an expandable bladder, which in turn expands into an oil-filled housing [40]. While it has been proven as a part of the Deep ESP, this technology samples 10 L of water at a time. For the VERNE project, a miniature version of the technology would require development [40].

C. Key Developments or Technology Gaps

The sample handling system for VERNE is unique in that no liquid handling system has yet been a part of a NASA mission, placing such systems at TRL 5 or less. Sample collection and in situ analysis has been done on autonomous systems in Earth's oceans and under ice [41,42], but with varying payloads, and little sample processing. Incorporating these sample processing procedures in small volumes, in conjunction with autonomous liquid sampling and analysis is novel and at current TRL less than 4; therein the potential work for VERNE in Phase II of the project involves benchtop testing of such a system, and advancing some of these technology gaps.

VI. Structures (STR)

A. Subsystem Requirements

The Structures subsystem is responsible for decisions involving the structure and configuration of the vehicle and investigating the mass budget of the vehicle. Several requirements of the Structures subsystem derive from the SESAME requirements: structure of the vehicle must accommodate all the systems in the vehicle bus and achieve a mass of 200 kg or less. Additionally, the structure must protect these systems from environmental factors including pressure, water ingress, and radiation, in order for the vehicle to proceed through the anticipated ice profiles. To support the scientific endeavor of water body profiling, the structure must separate or deploy an anchor, and maintain this anchor for the duration of the profiling operation. Finally, a system that terminates at this anchor and can repeatedly raise and lower the profiling section of the vehicle is required.

B. Structure Design

The vehicle design and breakdown of modules can be seen in Fig. 4. The vehicle is currently estimated to be approximately 4.5 m long, with an outer diameter of 34 cm, although the length is subject to change based on the design of interior components and addition of RTGs. The RTGs and power system not only drive the vehicle length, but also provide a constraint on the inner diameter of the vehicle - the diameter of the vehicle was chosen based on the diameter of the finless RTG concept with space for the thermal management system[43]. This model provides some critical early-phase information, such as the estimates of vehicle mass, particularly from the structural components.

Structural composites with previous flight heritage were considered; a carbon-composite honeycomb with aluminum face sheets has high TRL for space missions [44–46] and is advantageous for its strength-to-weight ratio, and even thermal insulation if the honeycomb is filled with insulating material [45]. This lightweight option is more favorable than a carbon fiber matrix or metal since these composite panels have heritage on other space missions and will help close the mass budget. Although radiation levels are expected to be dangerous for electronics on the surface

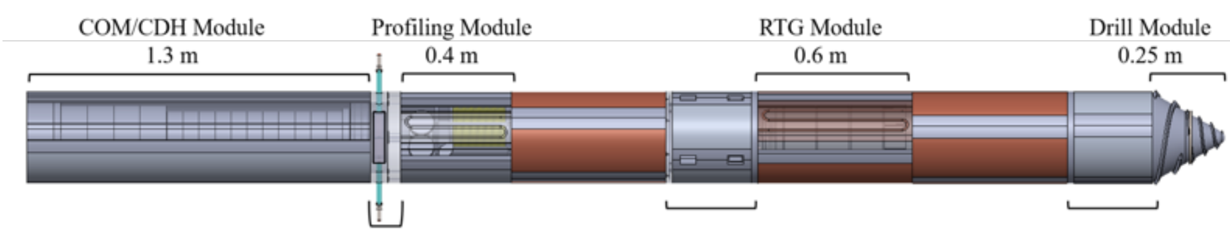

Fig. 4 VERNE vehicle conceptual design, with modules labeled as they are broken down by subsystem. This configuration is used in the mass budget study, and only uses three RTGs.

of Europa, below 10 cm of ice the radiation is expected to decrease significantly, allowing for radiation hardening of equipment rather than a structural radiation protection [47].

1. Separation System and Anchoring

Upon reaching a body of water, the upper section of VERNE will actively anchor itself into the ice to allow for profiling mode. This anchor ensures that a portion of the vehicle does not continue descending with the profiler so that communication can be maintained with the surface. It is anticipated that the anchor and a section of tether will freeze in the ice as the profiler descends; however, the anchor should support the profiler's weight if the ice around it does not refreeze before the profiler reaches the liquid water. The design for VERNE's anchor uses a pair of thermal spikes, which were chosen over scissor jack clamps that have been developed for a similar purpose by [48] due to the size and requirement for precise knowledge of borehole size and the interest in retractability. These thermal spikes, thin copper cylinders with embedded resistive heaters [49] are capable of melting laterally into the ice on either side of the probe. The development and testing of a lateral thermal spike anchor is the subject of ongoing work for the VERNE team, and a preliminary design of the system can be seen in Fig. 5.

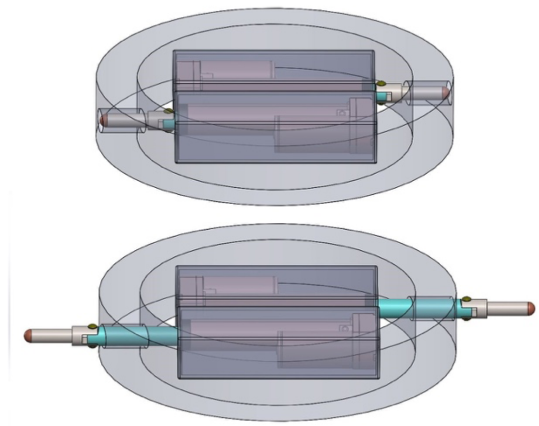

Fig. 5 Model of thermal pick concept. Linear actuators are located in a flooded section of the probe but encased to prevent corrosion.

2. Vehicle Profiling

The water body profile, which allows the vehicle to repetitively traverse 100 m through the ice-ocean or ice-water body interface, is made possible by a single separation of the vehicle that separates the anchor from the front section of the vehicle. A reinforced tether will keep the anchor and profiler in communication, as well as support the motion. This tether management system (TMS) that controls the profiling is one of the key technologies chosen by the VERNE team to explore and develop, and has led to a custom TMS comprising of an individually controlled spool and level-wind and a tension decoupling system using two grooved capstans [50,51].

C. Mass Budget

The mass of each subsystem is estimated based on extant relevant technology. This breakdown of mass by subsystem can be seen in Table 4. The mass budget does not account for the mass of the RTGs, per SESAME, but does account for the structure and thermal system that encloses them. In this budget, three RTGs are assumed for the vehicle; if more RTGs are needed, the structural and thermal management mass will increase significantly. The mass budget shows that with the technology the team has identified for the mission, the SESAME-derived 200 kg budget

Table 4. The mass breakdown of VERNE's subsystems; the mass was estimated based on terrestrial technology that can be applied to a Europa probe, and the budget accounts for a design margin that varies 10-15% based on the fidelity of the estimations.

Hardware		*Mass*					
Level 1 (Subsystem)		CBE(kg)	Contingency (%)	Allocated Mass(kg)	Subsystem Allocated Mass(kg)		
GNC + Drill					**34.5**		
	GNC + Drill Total	CBE + Contingencies (kg) =	**45.20**	Subsystem Margin (kg) =	-10.70		
COM + CDH					**30**		
	COM + CDH Total	CBE + Contingencies (kg) =	**34.21**	Subsystem Margin (kg) =	-4.21		
EPS					**0**		
	EPS Total	CBE + Contingencies (kg) =	**16.90**	Subsystem Margin (kg) =	-16.90		
THE					**15**		
	THE Total	CBE + Contingencies (kg) =	**67.05**	Subsystem Margin (kg) =	-52.05		
STR					**60**		
	STR Total	CBE + Contingencies (kg) =	**89.43**	Subsystem Margin (kg) =	-29.43		
SHS					**10.5**		
	SH Total	CBE + Contingencies (kg) =	**10.17**	Subsystem Margin (kg) =	0.33		
Totals:	Mass Requirement (kg)	Design Margin (%)	Adjusted Mass Requirement (kg)		**Total Allocated Mass(kg)**	**Margin (kg)**	**Margin (%)**
	200	25%	150		**246.07**	**-96.07**	**-64.05%**

cannot be met without further development. While opportunities for mitigation exist, such as material choice and size of external heating plates, developments in the communications system that result in a shorter vehicle, or developments in power systems that allow fewer RTGs to be used, would be more effective at optimizing vehicle mass.

D. Key Developments and Technology Gaps

Although the selected materials for the structure of the vehicle were chosen with high heritage, evaluation of these materials in water and with high external pressures is an identifiable technology gap. The structure and design that enables vehicle profiling is additionally a source of needed development; although similar anchoring in ice boreholes has seen testing [48], the use of thermal spikes for such an anchor is a new development that is less than TRL 3. Tether management systems comprising the components in the VERNE design are commonly used on Earth; however, development of a robust autonomous system in VERNE's form factor is likewise in need of development.

VII. Communications, Command and Data Handling (COMCDH)

A. Subsystem Requirements

The communication system on VERNE is responsible for returning telemetry and science package data to the lander on the surface of Europa, as well as maintaining the probe's ability to receive commands from ground control. This system must be highly redundant and capable of maintaining communication throughout the expected ice profile at a data rate at least that of the surface-to-Earth link. An achievable total data volume for a 20-day Europa surface mission has been estimated at 4 Gbits [52], so 0.2 Gbits per day was selected as a minimum data rate for this link.

B. Communication System Design

Melt probes used for geophysical research on Earth have historically communicated and often been powered over tether unspooled behind them as they descend [53–55]. This heritage lead to the selection of a fiber optic tether as the primary method of communication for VERNE. Fiber optic tethers are light enough that carrying even a 15 km spool is not a significant mass burden, and they are additionally able to provide very high data rates at low power. However, they are also very fragile; it has been suggested that the high level of geologic activity in Europa's crust (Fig. 1) or even the dynamic process of the borehole refreezing are likely to break a small fiber optic tether at some point during such an extended mission. Therefore, a secondary communication system comprised of wireless repeater "pucks" deployed regularly throughout the ice shell is also included in the design. This secondary system will have significantly lower data rates and higher power requirements but will ensure a link can be maintained if the primary system fails.

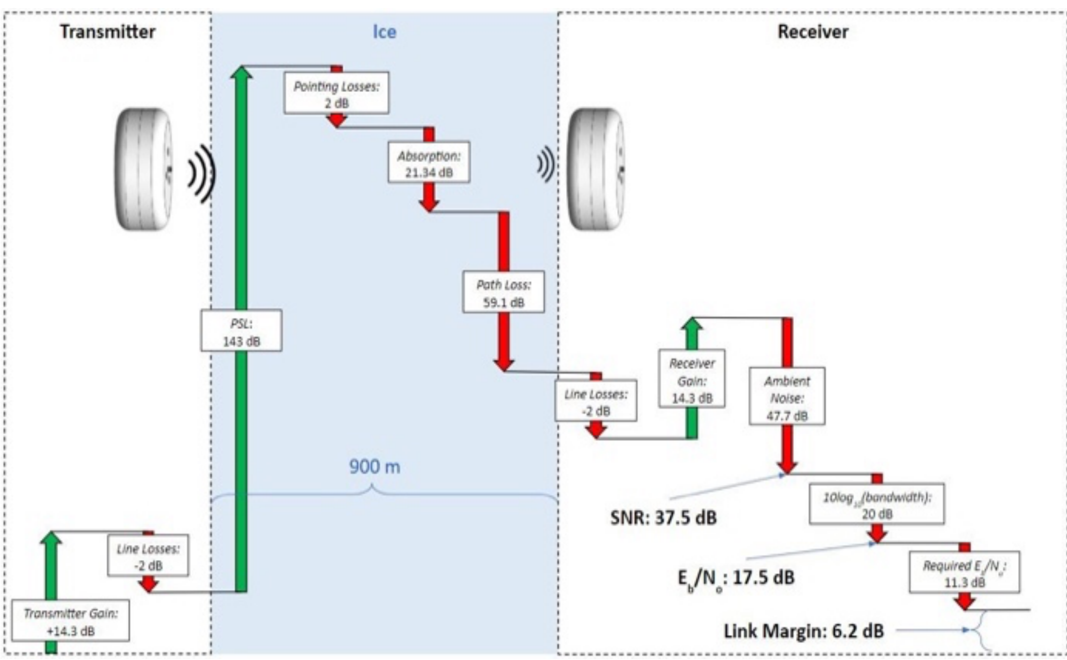

Fig. 6 Puck-to-puck acoustic link budget. The pressure spectrum level (PSL) was calculated using a transmitter power of 70 mW and a bandwidth of 100 Hz, and the absorption was calculated with a transmit frequency of 5 kHz.

The pucks will also be integrated with the tether so that the acoustic architecture only needs to close the gap across a break, reducing operational loads on the other repeaters in the system.

1. Attenuation Modeling

Both acoustic and Radio Frequency (RF) communication (i.e. electromagnetic waves in the RF and microwave spectrum) have been proposed for communicating through in the past (See [56–58] for RF, [59] for acoustic). For this design, attenuation models of both signal types were analyzed in order to identify a preferred technology [60–65]. The models account for differences in ice temperature and impurities, but in both cases frequency has a dominating effect; higher frequencies experience much higher attenuation. This introduces a design challenge because both antennas and acoustic transducers grow in size as their resonant frequencies decrease. The decision to pursue an acoustic communication system was chosen for two reasons: 1) Preliminary helical RF antenna design threatened to increase the diameter of the probe, and 2) RF signals travel well through cold, dry ice, but are reflected or absorbed by water, ice-water mixtures, and salt mixtures, each of which may be encountered during the mission.

A low-frequency signal in the audible range was selected as the carrier. Although higher frequencies enable higher instantaneous data rates, current modeling shows that decreasing the transmit power (and therefore increasing the transmission time achievable with a fixed power supply) is a far more effective way of increasing the total data volume. An example link budget showing several communication parameters and sources of loss is shown in Fig. 7. Estimates for ambient acoustic noise are from [66], while the required Eb/No to achieve a bit error rate of 1×10^{-6} was determined using methods described in [67].

2. Repeater Design

Physically, the repeaters are small disk-shaped pucks that transmit and receive acoustic signals using piezoelectric acoustic transducers. Each puck contains one or more low-temperature, long-life lithium batteries and electronics for both acoustic and fiber-optic signal repeating. Pucks deployed in the upper, colder region of the ice shell contain RHUs to warm the electronics. These components are surrounded by a thin structural layer, a thicker layer of thermal insulation, and an outer shell comprised of Delrin. The current piezoelectric transducer design is a thin, lead-zirconate-titanate (PZT) ceramic disk with polyurethane insulated electrodes. An aluminum backing helps to reflect acoustic energy forward [68] and the Delrin shell provides good acoustic impedance matching with ice. An aluminum backing helps to reflect acoustic energy forward [68] and the Delrin shell provides good acoustic impedance matching with ice. Screws threaded into the aluminum backing are used to press the layers together and to pre-stress the ceramic, a technique which has been shown to improve performance in very cold ice [69]. The puck external dimensions and an exploded CAD view and thermal analyses are shown in Fig. 7. An acceptable internal temperature is achievable for the uppermost puck, although there still exists a need for design efforts toward low-temperature electronics.

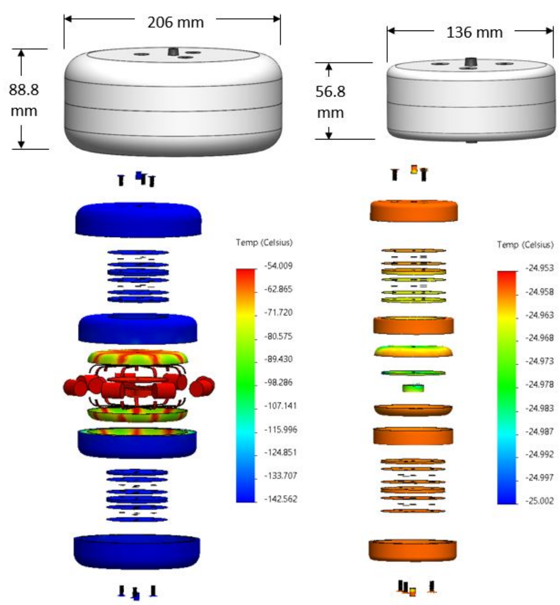

Fig. 7 Acoustic repeater puck CAD, showing a heated puck (left) and an unheated puck (right). Thermal analyses were performed for the first puck deployed 900 m deep in the ice shell and the fifth puck deployed at 4500 m (130 K and 250 K, respectively, for a convective ice shell model, Fig. 1).

3. Secondary System Capabilities

The capabilities of the communication system can be derived from the link budget. The attenuation model indicates that the pucks transmitting at the specified power and frequency can close a 900 m gap, which means that 16 pucks will be required for the entire 15 km descent. Using quadrature phase shift encoding (QPSK), the pucks will be able to transmit 10 kbits per second over the 5 kHz carrier frequency. The total data volume that the secondary communication system can transmit, however, is dependent upon the puck power supplies. A primary lithium battery with an energy density of 706 Wh/L and a minimum temperature of -55℃ was selected to fill this role, and the data volume was estimated using the link budget power and data rate, reasonable assumptions about battery self-discharge and idle power draw, a data-bits-to-bits-transmitted ratio of 2/3, and a total transmit efficiency of 42% (arrived at by assessment of piezoelectric transducer and amplifier efficiencies). By filling all available volume with the selected batteries 5.1 Gbits of data may be returned after the point of a tether failure. To meet the specified 0.2 Gbits per day for the entire mission (i.e. if the tether breaks immediately) requires a battery roughly the size of the entire puck, which is infeasible given the current design and has been noted as a critical technology gap. Fortunately, the probe will communicate solely over the fiber optic link prior to any potential breaks, increasing the actual data volume relative to this puck-only scenario. Better information on fiber-optic tether failure - which could be used in a failure rate analysis - is the subject of current research by the Europa STI project lead by John Hopkins University's Applied Physics Lab [70].

C. Key Developments and Technology Gaps

The development of these acoustic repeaters is an important step forward in ensuring the reliability of data transmission through Europa's ice shell. No published work exists so far on the transmission of digitally modulated data using acoustic waves through ice, but the basis for the technology exists in the extensive work done on underwater communications [60,66,71] and the use of acoustic signals for in-ice sensing and measurement [61,69,72]. This qualifies it for TRL 3 and motivates the VERNE project's interest in further study of such devices. Another area of development that is needed to support the acoustic transceiver design is the puck power supply; while the assessed battery technology is not capable of meeting the data volume requirements, this gap could be closed by employing higher energy density batteries or batteries with lower operating temperatures. Finally, while piezoelectric transducers have been embedded in ice and operated in the field and are relatively high TRL [69], they have generally been custom designed for a given device or application and thus have also been selected for further study moving forward.

VIII. Guidance, Navigation, and Control (GNC)

A. Subsystem Requirements

In order to penetrate the expected ice shell profile on Europa, and deliver the vehicle through 15km within three years, VERNE must have a drill capable of operating in and traversing the expected ice environment while also having the ability to navigate through any expected obstacles. As the drill is the primary method of propulsion as well as descent control, the GNC team is responsible for its design and implementation as well as traditional GNC responsibilities such as position and attitude determination, attitude control and obstacle avoidance.

B. GNC System Design

The VERNE GNC sensor suite includes options for attitude, position, and rate determination as well as processors. The suite incorporates Commercial Off-The-Shelf (COTS) components, and most of the selected components have some degree of space heritage – for example, some of the components have been used in small and medium sized satellites, or else used or tested on autonomous underwater vehicles for similar purposes, resulting in relatively high TRL. Overall, these components have been selected to have low mass and power requirements while maintaining high accuracy measurements.

As the drill head rotation is decoupled from the rest of the vehicle (to prevent spinning of the upper non-rotating section of VERNE), an anti-torque system must be considered. Counter rotating drill heads will reduce counter-torque required, but additional techniques must be utilized to completely reduce counter-torque. A design trade space consisting of field tested units narrowed selection to two options suitable for VERNE's operations: skate blades and leaf springs, with the inclination towards leaf springs due to its ability to alter its maximum extension [75], although further experimental analysis is needed to determine final system choice.

1. Drill Design Concept

Multiple prior designs for subsurface ice drilling and were reviewed to conduct a trade space study for an optimum drill. The study yielded five primary methods of drilling – pure melting head [52, 54-55], hot water jets [69], pure mechanical-rotary and or rotary- percussive (surface drills on Mars)[73], and hybrid-melting with mechanical drilling [74]. A design trade space was then developed identifying important characteristics and assigning them values based on their relevance to VERNE. It should be noted that the conditions under which these designs were tested to determine descent rate are different than those found on Europa: only SLUSH was tested in cryogenic ice ; VALKYRIE, IceMole, and CHIRPS were all tested in glacial ice at about -10℃ to -20℃ [54,55,57,74]. The main factors that were used to evaluate each design were efficiency of drilling, interference with sample collection, power requirement, and mass.

Although a melting head (a dome-shaped mechanism that transfers thermal energy to the ice in order to melt it and clear a path through it) is an intuitive solution due to the available waste thermal heat from RTGs, it has shown to be the least efficient in terms of power required to achieve a given descent rate. Hot water jets, which fire high temperature, high pressure water at the ice, are more efficient. However, the most efficient methods are mechanical, with studies showing that percussive drilling (breaking off ice chips with blunt pieces mounted in the drill bit) outperforms cutting (slicing off ice chips with blades in the drill bit).

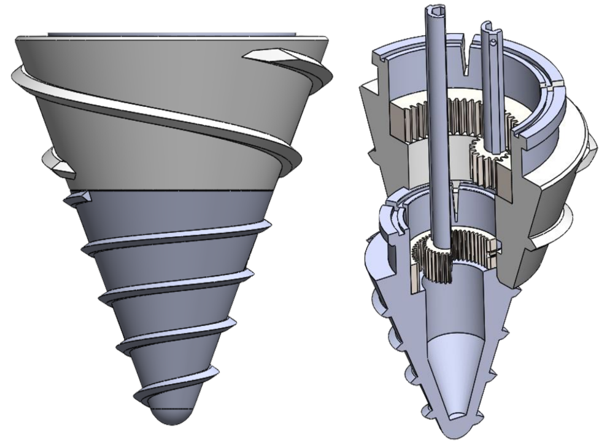

Fig. 8 Design of the mechanical drill head for VERNE showing counter-rotating components and internal hollow structure for heat transfer

Regardless of efficiency, purely thermal components cannot be expected to penetrate any rock or salt layers [34,35] that may be encountered during the mission. Hot water jets can be easily switched on and off, so an array of jets could be used to selective apply heat and pressure to blast debris out of the way or to steer the probe by gradually slanting the melt channel. However, the mission's motivation relies on the sampling and analysis of water periodically through the descent, and strong water jets increase the mixing of the water in the melt pocket, increasing the uncertainty that a sample at a particular depth accurately represents the ice shell at that depth. The study thus resulted in the selection of a hybrid thermo-mechanical drill that can utilize the excess thermal heat to melt through the ice shell, while also enabling the vehicle to penetrated solid deposits in the ice shell using mechanical drilling.

The current design (Fig. 8) includes a rotary drill consisting of counter-rotating components to reduce counter-torque[74], utilizing dual motors for precise control of each rotating component. Internal fluid loops will deliver heat from the RTGs to the drill head. The drill head will be nominally composed of aluminum, chosen for its low density and high thermal conductivity, while the blades will be embedded with harder tungsten carbide. The precise parameter selection for blade size, length, and rake angle is currently in development.

C. Key Developments and Technology Gaps

Current applications of thermo-mechanical drills have been tested in laboratory environments including the study of long-term drilling effects on its thermal and mechanical efficiency, but have yet to progress to regular use, thus achieving a TRL level of 3-4. Honeybee Robotics is currently developing a drill for use on icy worlds [74]. Anti-torque systems are currently used for mechanical drilling in terrestrial environments, but questions arise on their reliability for long term uses in a saline environment (TRL 5-6).

IX. Electrical Power Systems (EPS)

A. Subsystem Requirements

The Electrical Power Subsystem (EPS) is responsible for providing, storing and distributing electrical power within VERNE. VERNE uses the heat and power estimates of finless RTGs described in the SESAME call as its primary source of both thermal and electrical power, chosen to provide a robust, self-contained power source that has proven flight heritage, possibly enabling the launch of the mission much sooner than a lower TRL alternative such as a fission reactor.

B. Power Budget

The baseline design of VERNE was modeled based on 3 RTGs, each providing a relatively constant output of 100 W_{elec} throughout the mission lifetime. Table 5 shows the electrical power budget broken down by each operational mode, which directly correspond to the modes of concept of operations. During collection of scientific samples or communicating with the spacecraft, all the excess electrical power (after life-keeping functions) is directed to the drill to minimize the time required to traverse 15 km of the ice shell. Once the vehicle reaches the ice-water interface and is taking samples in the water body, there is a large surplus of electrical energy (as the drill is no longer needed). Using

Table 5. Power Budget by Operational Mode

		Safe Mode	Science Mode	Comm Mode	Water Profile Mode	Drill Mode
Hardware	*Power*					
Level 1 (Subsystem)	Contingency (%)	CBE Power Draw(W)	CBE Power Draw(W)	CBE Power Draw(W)	CBE Power Draw(W)	CBE Power Draw(W)
GNC + Drill	15%	5	85	160	10	470
COM + CDH	25%	1	1	4	4	1
EPS	25%	2	2	2	2	2
THE	15%	10	15	15	10	15
STR	25%	0	0	0	0	0
SHS	25%	0	5	1	9	1
PAY + SCI	25%	5	70	5	70	5
Totals:	Total CBE + Contingency	28	222	222	137	583
	Margin (W)	197	3	3	88	-358
	Margin %	87%	1%	1%	39%	-159%
	Number of RTGs	Total Power (W)	Power Margin (%)	Available Power (W)		
	3	300.00	25%	225.00		

current models calculating the thermo-mechanical drill power consumption, traversing 15 km within three years in the Europan ice environment would require an average of 470 W_{elec}, creating a power deficit, as this is more than the three model RTGs alone can provide.

C. Key Developments and Technology Gaps

This power deficit is a technology gap that arises from the low power density of RTGs and the significant power requirements of the drill. To address this, the number of RTGs on the vehicle could be increased to generate sufficient power to traverse 15 km in three years, but this would result in increasing the size of the vehicle that exeeds the SESAME mass requirement. Alternatively, the drill could operate at a lower power consuming mode using only 3 RTGs, but the vehicle would then not meet the SESAME requirement of traversing 15 km within three years. Both of these requirements could be met simultaneously if the tether also provides power from an external source on the surface connected to the vehicle for the first few kilometers, since these are the most power consuming to traverse due to the temperature profile of the ice. Secondary power generation mechanisms using the heat leftover from the RTGs were considered and determined to be far too inefficient to be feasible.

Assessment of Battery Necessity and Application

On VERNE, RTGs provide nearly constant power over the mission lifetime, and the vehicle consumes near constant power across operational modes by diverting all excess power to the drill. This makes a significantly sized battery unnecessary, although batteries and capacitors will be used to regulate current and voltage being sent to subsystems and components. Additional functions include smoothing transients in power supply and demand, and ensuring electrical components receive power within their designed current, and voltage operational ranges. To operate effectively in the cold Europan environment, low temperature, high power density Lithium Ion batteries for space applications will need further technology development from their current laboratory state of TRL 3.

X. Thermal Systems (THE)

A. System Requirements

The thermal system in VERNE functions as an environmental regulation system maintaining sensitive electronics and instrumentation to within set temperature limits and is integral to providing thermal power for the drill. Each component has its own upper and lower limits within which it can operate, which the thermal system uses as constraints. However, internal temperature is not the only regulation needed by the thermal management system; due to the temperatures in Europa's ice shell, the thermal system must actively prevent the vehicle from freezing into the shell by regulating the surface temperature of the vehicle such that the surrounding melt pocket remains liquid. Finally, as VERNE's drill system uses a thermal melt head in conjunction with its mechanical drill, the thermal system will need to redirect large amounts of waste heat from RTGs to the drill head. These three requirements - maintaining instruments within their operable temperature range, maintain the external temperature of the vehicle to prevent freezing, and delivering thermal energy to the drill head to sustain the desired descent rate – are the responsibility of the single system, introducing the need for a large design that spans the vehicle.

B. Thermal System Design

To meet all requirements using RTGs as the sole power source, a mechanically pumped fluid loop has been designed. A pumped fluid loop (PFL) is the only heritage thermal control system that NASA has flown with RTGs on interplanetary missions. PFLs are active thermal control systems that use a fluid to redistribute heat. The PFLs used with RTGs are single phase systems, meaning they do not employ evaporators and condensers. VERNE's system uses CFC-11 as its fluid and a combination of copper and aluminum for pipes and fittings. A diagram of the flow path is shown in Fig. 9. Heat is collected from the RTGs by the fluid loops and diverted directly to the drill head through internal fluid loops (illustrated on the left of the vehicle), insulated to ensure heat loss is minimal. After interacting with the drill head, the flow is directed through both the interior of the vehicle and exterior hot plates to maintain instrument temperatures and remove heat from the loops, respectively. The flow path additionally has an option to bypass any of these features to allow greater control. Bypasses allow heat flow to be directed toward any component approaching its lower temperature limit rather than using secondary loops to service all modules of the vehicle. This creates a more complicated control system but saves on the large amount of extra mass and volume that would be required for secondary loops.

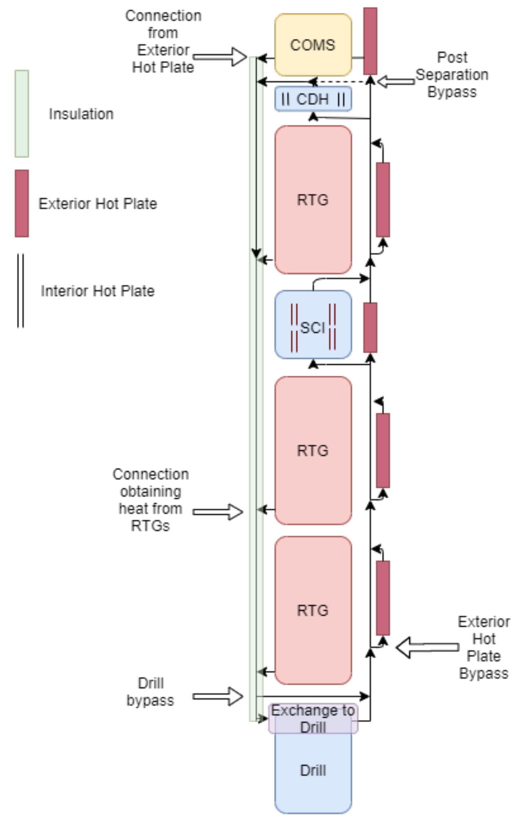

Fig. 9 Pumped fluid loop design flow diagram. Heat is directed from the RTGs first to the drill head, and is cooled as it ascends the vehicle using exterior hot plates.

Hot Plates

Throughout the vehicle, the PFL interacts with both internal and external hot plates. Internal hot plates are the standard for how a PFL interacts with electronics and instruments; heat flow is passed through one end of an aluminum plate on which an instrument is mounted. To address the concerns of maintaining a melt pocket and the issue of heat rejection without radiation, this hot plate design (Fig. 10) has hot flow passing through them, and instead of conducting heat to an instrument they reject heat to the Europan ice shell.

Each exterior hot plate unit consists of four curved plates evenly spread around the circumference of the vehicle, as seen in Fig. 10. Flow branches to pass through each plate and then reconnects after each hot plate unit. The plates are aluminum and mounted into structural honeycomb panels. In between the structural panels and the hot plates, ceramic insulation keeps the external heat rejection and internal bypass loops thermally isolated.

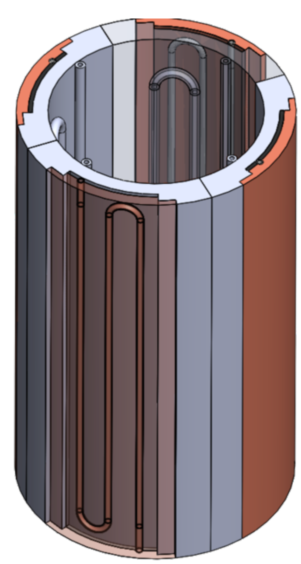

Fig. 10 Example module structure with external hot plates and fluid loops

C. Key Developments and Technology Gaps

As it currently stands, the thermal control system is mass intensive and has not been optimized for performance and mass. The external plates contribute a large percentage of the mass and make the thermal system far heavier than most existing space flight thermal systems. The design currently uses copper and aluminum for its primary materials as they are well tested with CFC-11 and optimal for their thermal properties. Due to the complexity of the system and mass concerns, opting for additively manufactured titanium panels and piping is an option that is currently being considered. Being able to 3D print most of the system allows for mass saves on both the material being lighter and have fittings completely integrated into the system. In order for the material switch to be viable, irradiation and corrosion testing will need to be done with CFC-11 and titanium and the system calculations will need to be redone to ensure there is sufficient margin.

In addition to the qualification of new material combinations, the PFL interaction with the drill head needs to be further developed; its current design uses eight parallel flow paths winding through the stationary internal section of the drill. This optimizes heat transfer from the PFL but requires that each path has its own pump, contradicting existing PFL systems in which only one pump is operated at a time with a backup present on standby. A scale model of the PFL interaction with the drill heat will need development and testing to verify the simultaneous operation of pumps in the system.

XI. Recommended Developments and Technology Maturation

After a high-level analysis of the components and technology needed to fly a VERNE-type mission was completed, the team compiled a list of what technology may be ready to fly with minimal development, and what technology needs extensive further development before conducting a mission, such that recommendations could be made for prioritizing development over the next decade. Some technologies, such as the separation system, structure material, or mechanically pumped fluid loops, have been flown or used in previous missions, but their applicability to an underwater environment would need verification. Other technologies, such as the hybrid mechanical and thermal drill, are in research and development stage, as they have not been proven at scale or in a similar environment, and can be considered TRL 3 or lower [74]. Table 6 lists key technologies supporting this mission that are in need of further development before a Europan probe mission.

Table 6. List of technologies in need of development by subsystem, with current technology readiness level (TRL) and current use.

Subsystem	Technology In Need of Development	Estimated Current TRL
Sample Handling System	Autonomous liquid sampling	5 [42,75,76]
	Sample Processing (Desalting)	3-4 [37][37]
	Sample Processing (Depressurization)	4 [40][31]
	Sample Processing (Concentration)	3 [77]
Structures	Vehicle Profiling	5 [78][41]
	Horizontal thermal pick anchoring	3 [49]
	Anchoring in ice borehole	3 [48]
Communication	In-ice acoustic data scheme	2
	Compact in-ice acoustic transducers	5 [68,69]
Guidance & Navigation	Thermo-mechanical drill	3 [74]
	Anti-torque system	5 [79]
Power	Finless RTG	2 [43]
	Low-Temperature Batteries	4 [80]
Thermal	External hot plates in water	3 [81]
	Drill Heating Mechanism	1 [74]

VERNE: Moving Forward

As a conceptual study, the VERNE project will not mature all of the necessary technology. However, selected areas of general development that the project will address in Phase II of its two-year period of performance include some of those needed to realize the unique aspects of the mission. Several technologies that are currently at TRL 3 or lower have been selected by the VERNE team for development, including the acoustic secondary communications system, the sample handling system, and the design of structures mechanisms that enable the profiling operation. Throughout the remainder of the project, the team will design and create benchtop systems to further the technology to at least TRL 5. The goal of the VERNE project is to identify and address these key technology gaps to prove the feasibility of a near-future mission to search for life under Europa's surface, without needing to wait multiple decades for the development of futuristic technologies.

XII.Acknowledgments

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