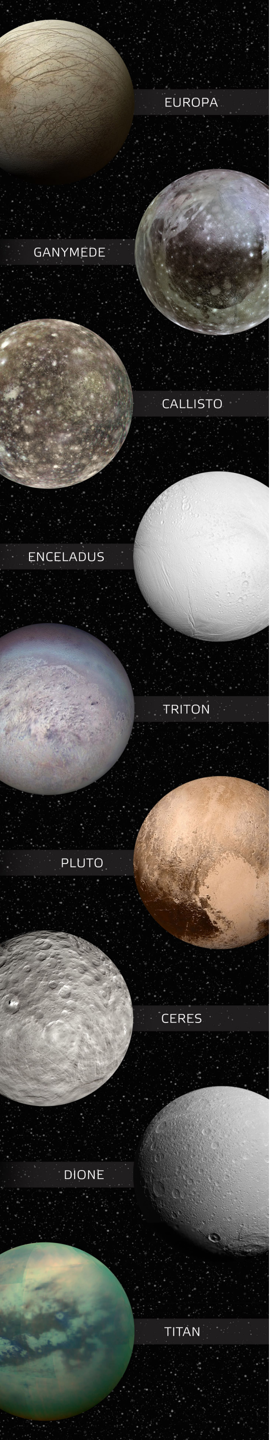
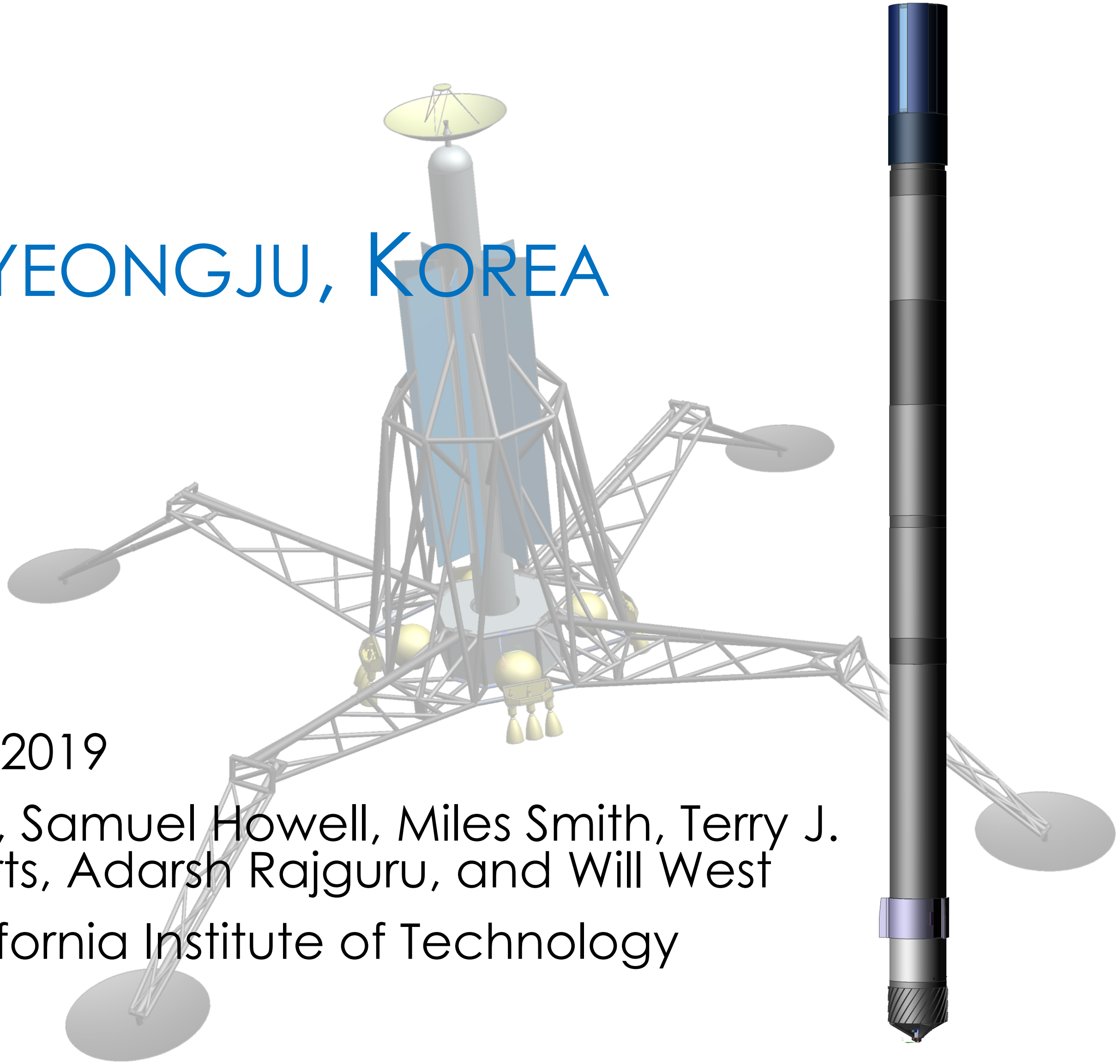



# Exploring the Solar System's Ocean Worlds with Thermoelectric Power Systems

## ICT2019, Gyeongju, Korea



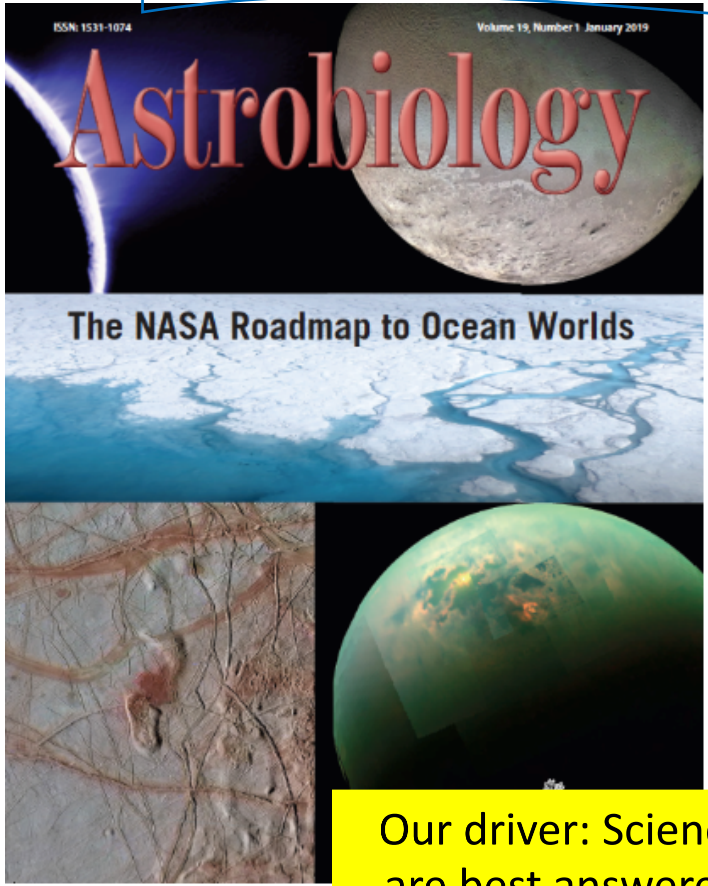
July 4, 2019

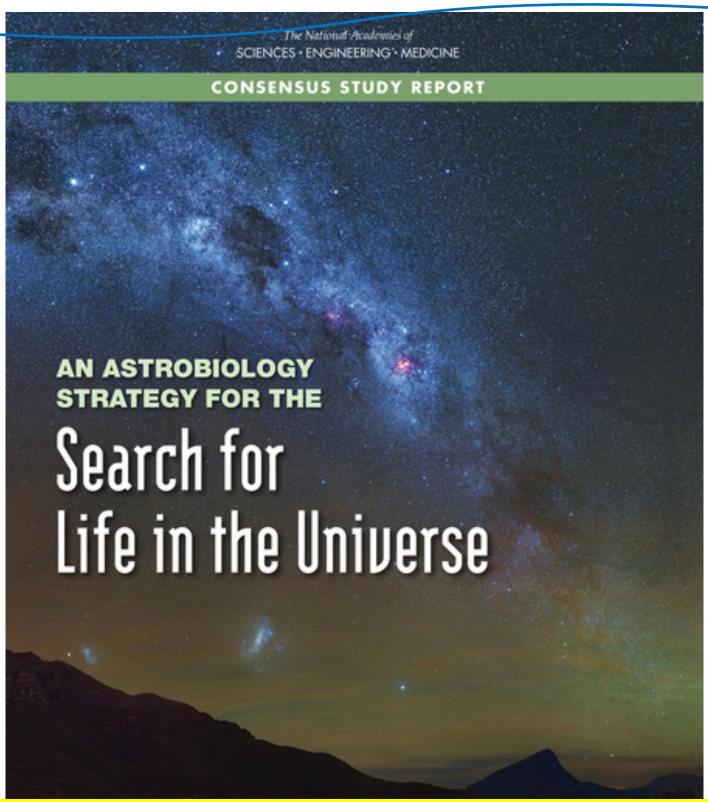
Jean-Pierre Fleurial, David F. Woerner, Samuel Howell, Miles Smith, Terry J. Hendricks, Bill Nesmith, Scott Roberts, Adarsh Rajguru, and Will West

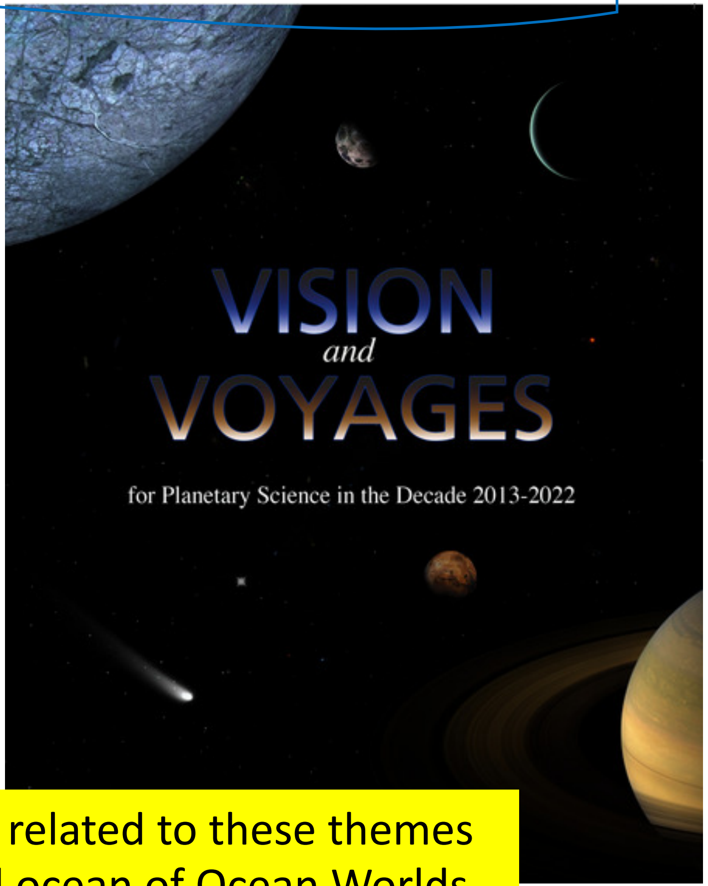
Jet Propulsion Laboratory, California Institute of Technology

# A Timely Goal

**To descend beneath the ice of ocean worlds, characterize their subsurface, their habitability, and search for life.**




Our driver: Science community's recognition that many key questions related to these themes are best answered through in situ analysis of the ice shell interior and ocean of Ocean Worlds

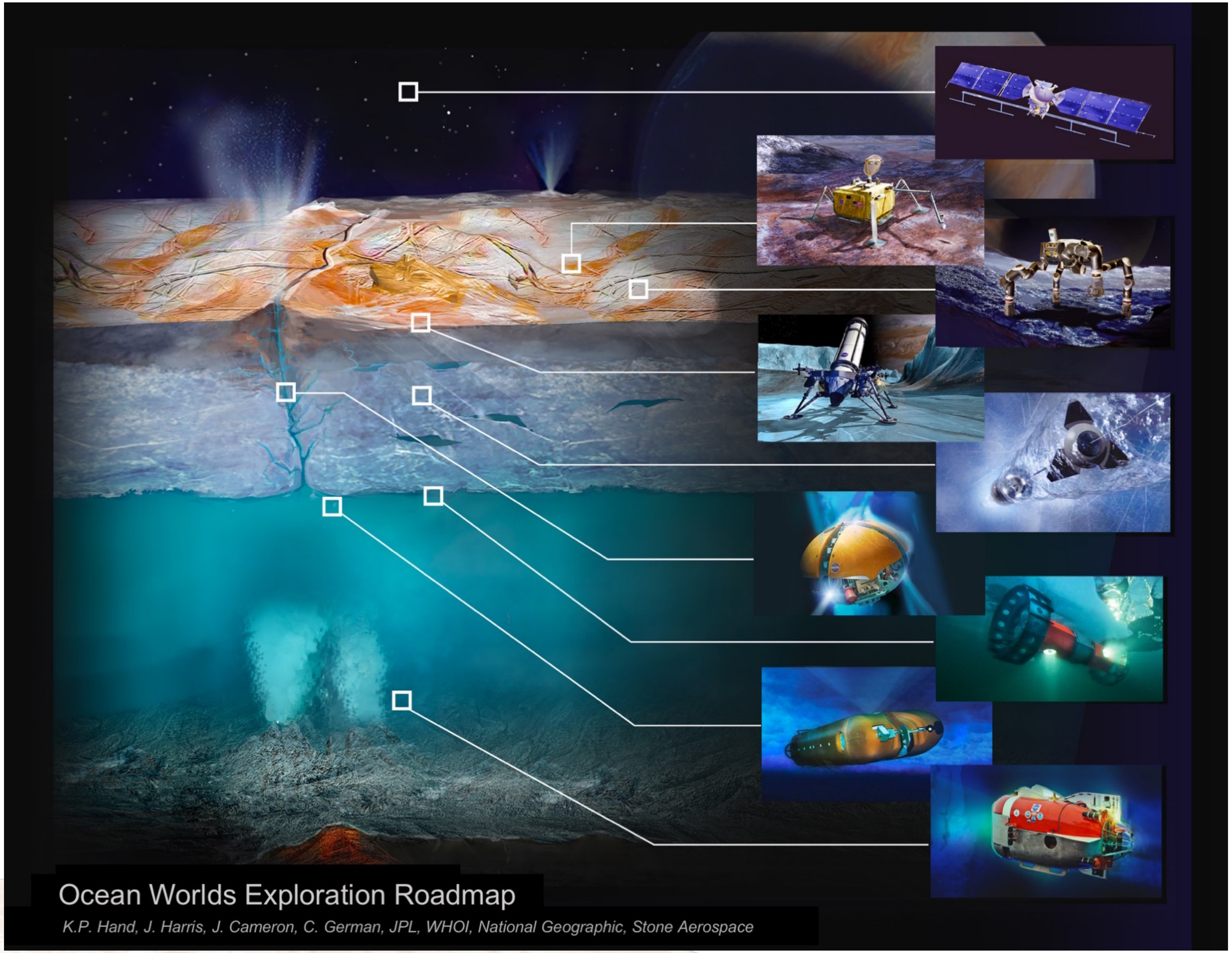
# A Potential for Life

Energy Source

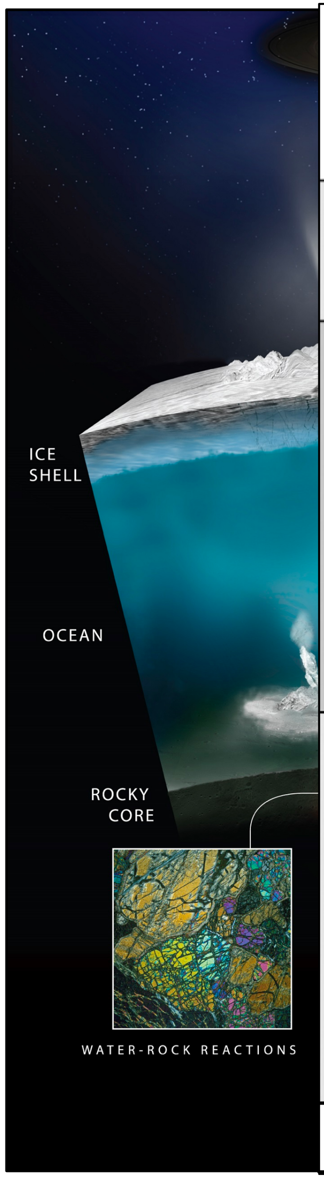
Biologically Essential Elements

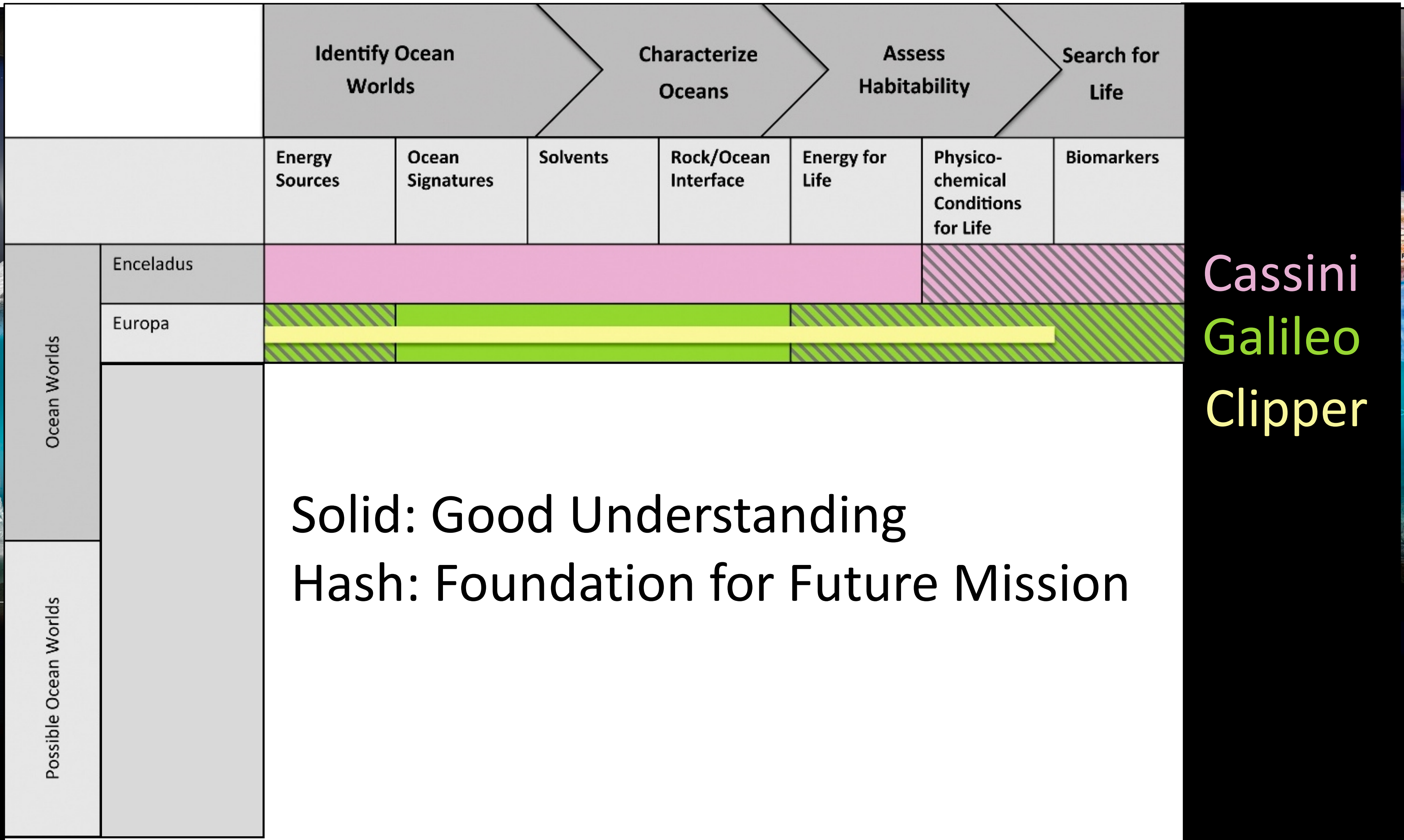
Liquid Water

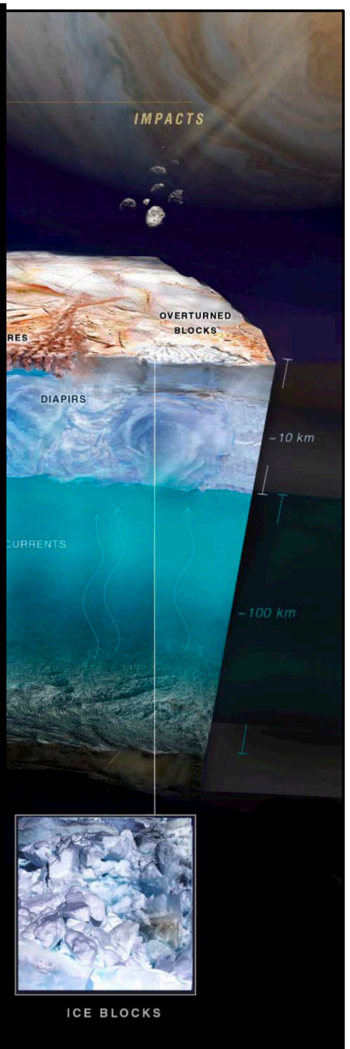
Time



# How many worlds support extant life?



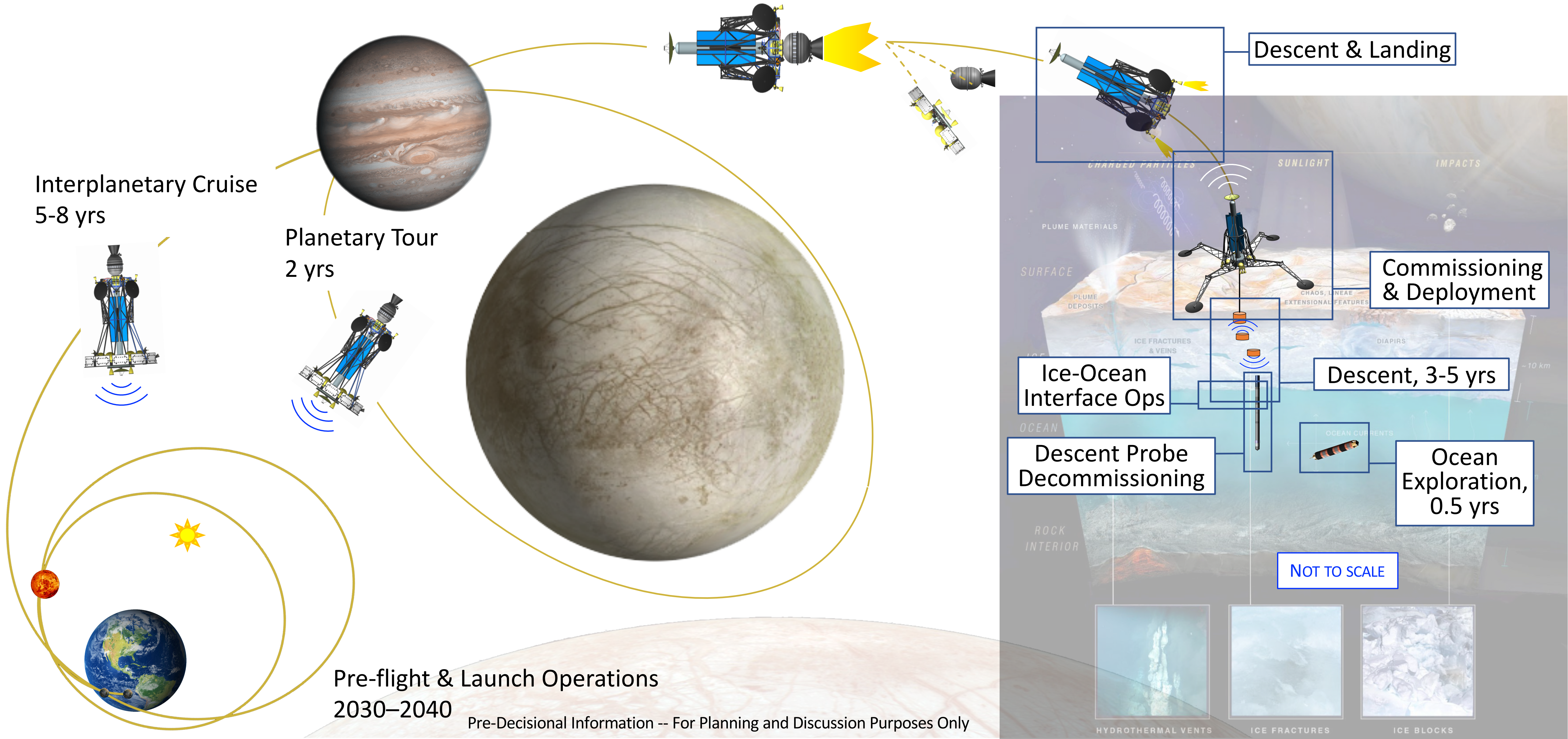




Artists' Concept


4

# Notional Mission Architecture



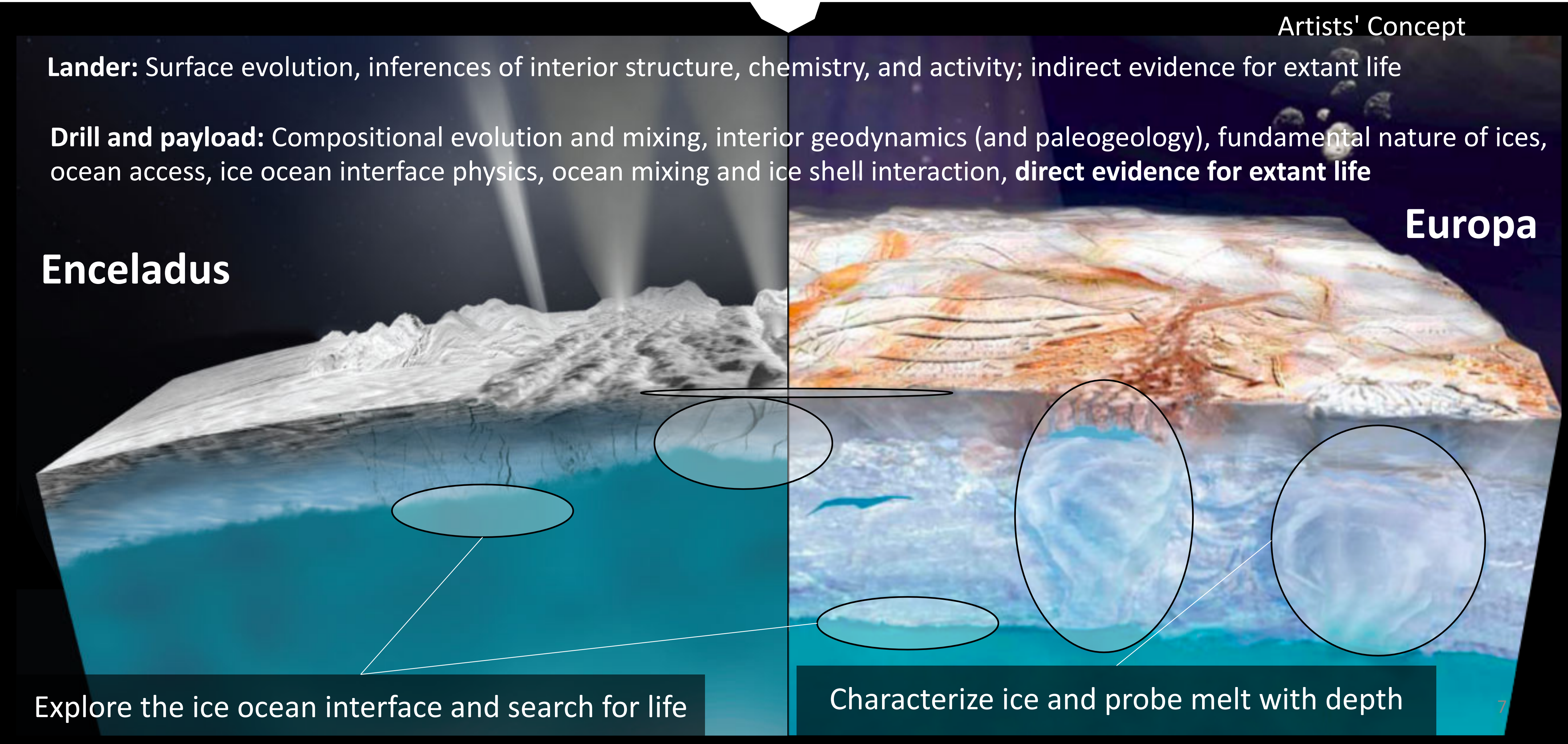

Pre-Decisional Information -- For Planning and Discussion Purposes Only

# Extreme Environment of Ocean Worlds

# Science Exploration Goals

**Lander:** Surface evolution, inferences of interior structure, chemistry, and activity; indirect evidence for extant life

**Drill and payload:** Compositional evolution and mixing, interior geodynamics (and paleogeology), fundamental nature of ices, ocean access, ice ocean interface physics, ocean mixing and ice shell interaction, **direct evidence for extant life**



# Studies: Key Challenges illuminating Technology Needs

*Getting There*

- Thermal control
- Mass and volume constraints
- Planetary Protection
- Precision landing

*Surface Initiation*

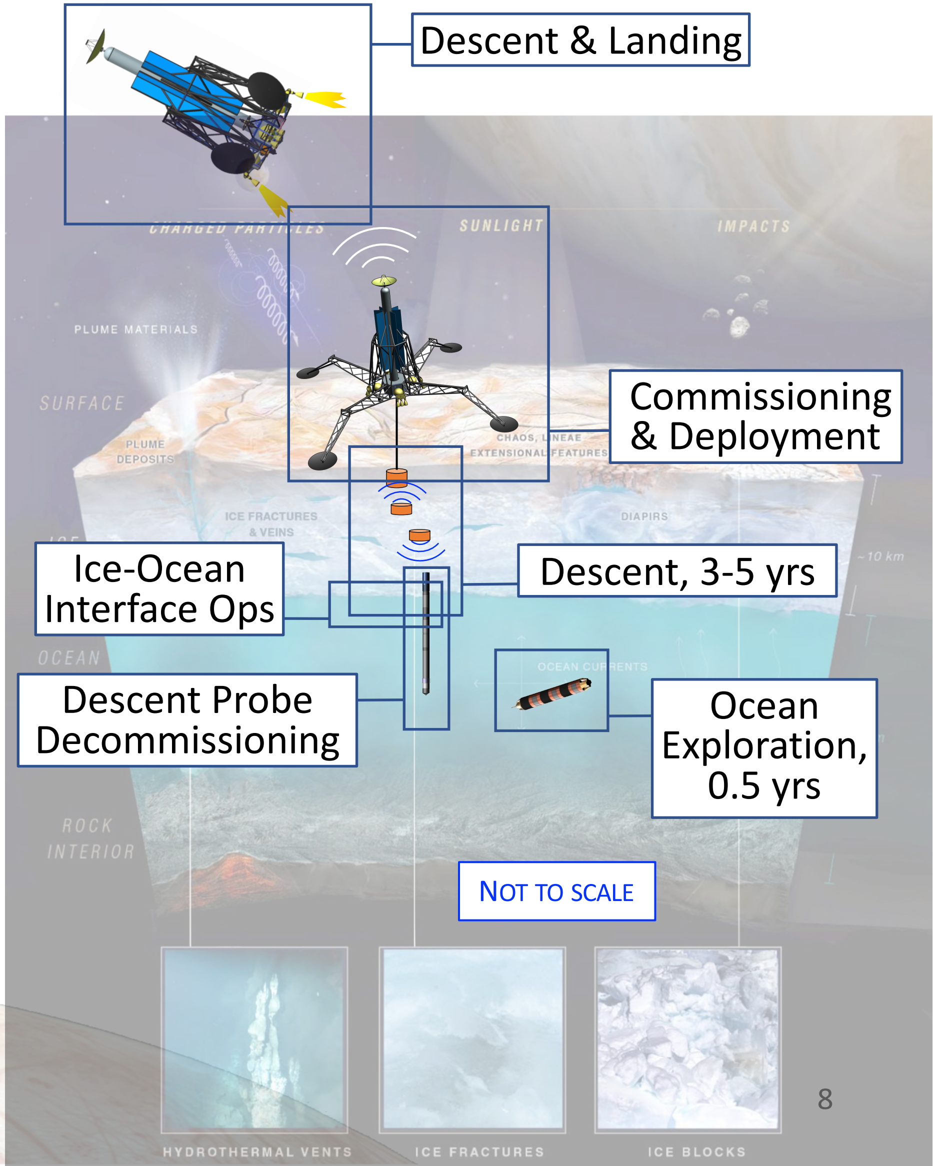
- Deployment mechanisms and processes
- Startup phase on cryogenic ice surface

*Ice Shell Penetration*

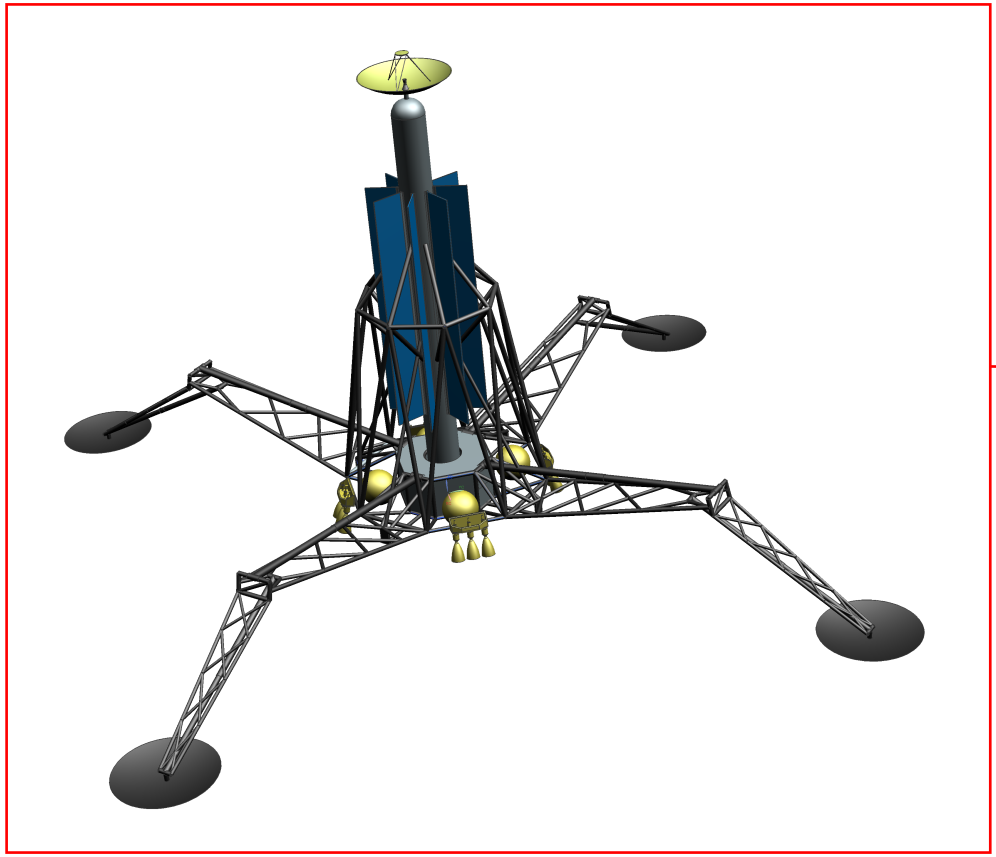
- Autonomous operations, communication architecture
- Detecting and avoiding in-ice hazards
- Hybrid drill/melt head that integrates, imagery and illumination, heat transfer, and sonar

*Ocean Exploration*

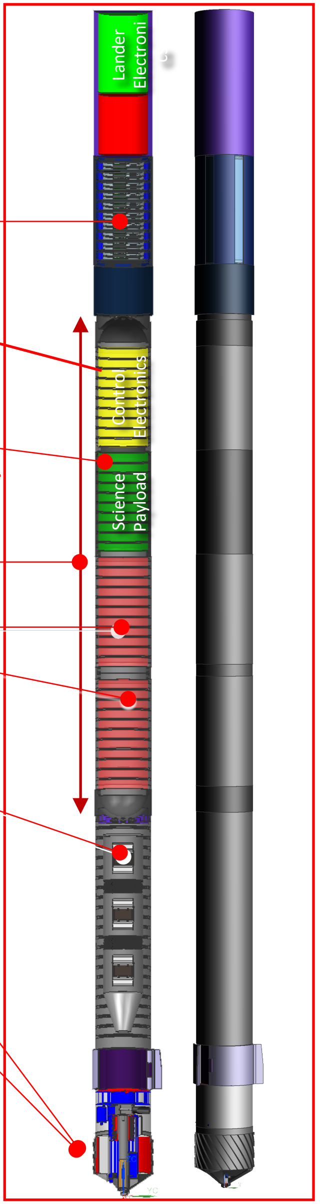
- Reliable anchoring before reaching the ice/ocean interface
- Deployment and operation of ocean explorer



# System Conceptual Design – Notional Overview



| Technology Categories |
| --- |
| Communications |
| Command and Control, autonomy |
| Pathfinding and Navigation |
| Science Observations |
| Thermal Control |
| Planetary Protection |
| Pressure Vessel |
| On-board thermal & electrical power |
| Ocean Explorer Probe |
| Ice penetration performance prediction |
| Active melting and debris removal |



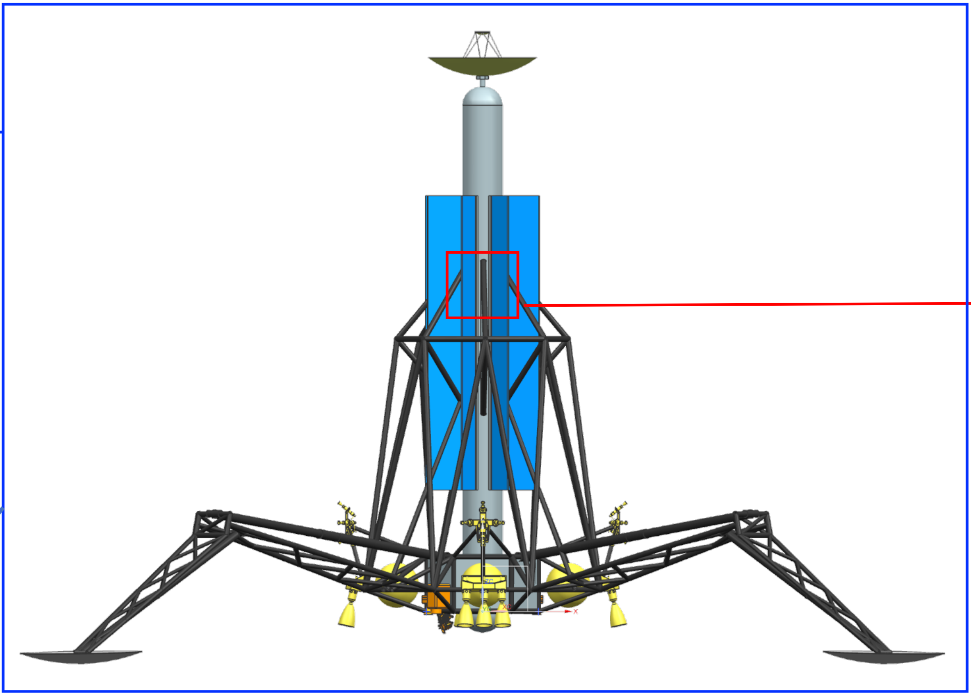

➢ Advanced Thermoelectric Generators would provide necessary on-board thermal & electrical power

# Key Technologies Under Consideration: Getting There

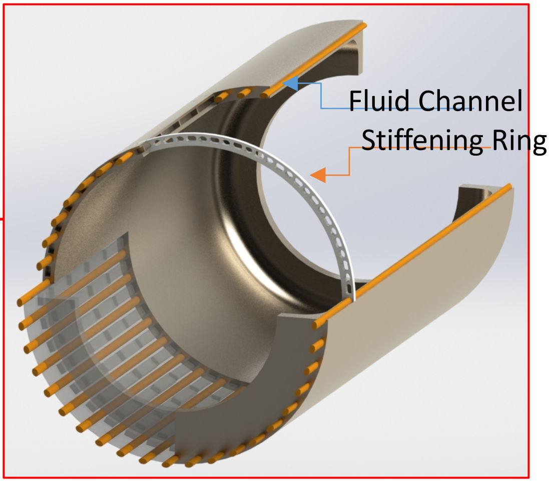
*Planetary Protection* trades related to sterilization strategies for lander, descent probe (external/internal)

Integrate with Contamination Control and develop plans for technology demonstrations

*Cruise Power* trades related to solar power versus direct feed from descent probe's on board thermoelectric power

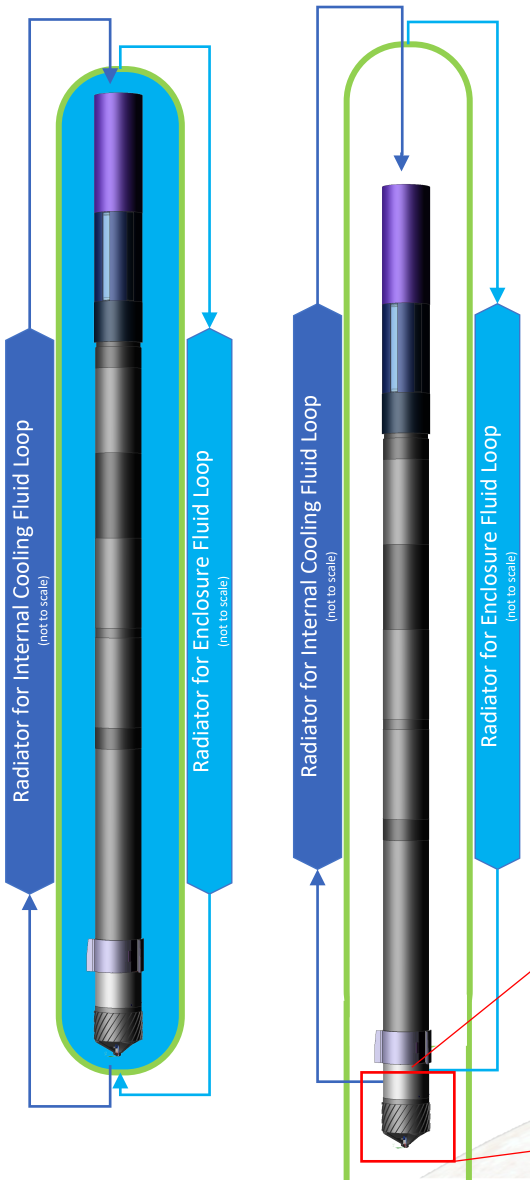


*Thermal Control* design and performance model for embedded adaptive loop heat pipe system integrated with thermoelectric generators(s) and external vessel.



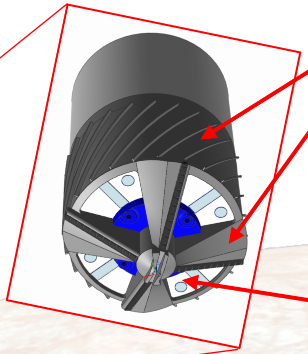

Pressure vessel cutaway

# Key Technologies Under Consideration: Surface Initiation




**Transitioning from Cruise configuration to Ice Penetration configuration**

- Deploy pressure collar
- Drain hot enclosure
- Deployment and startup of ice penetration concentrates on:
  - drill head design without melting or water-jetting (potentially),
  - sublimation in a pressure collar,
  - anti-torque mechanisms to react cutting forces in low gravity.

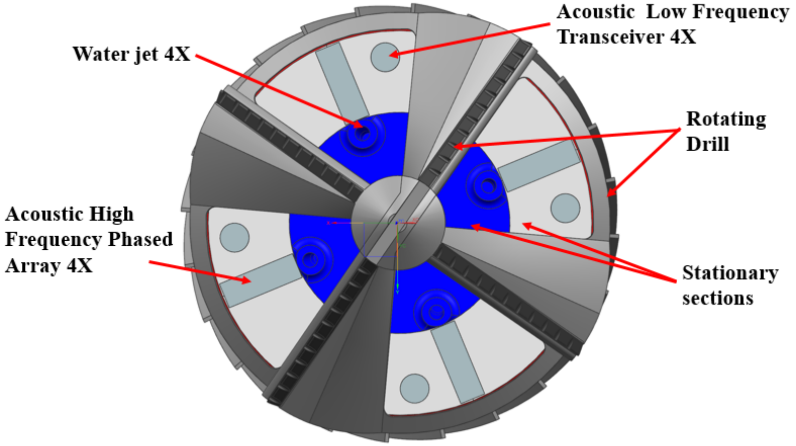



*Initiation* transitions to:

Melting, cutting, and water jetting

Depositing lander electronics

Relay telecom checkout



# Key Technologies Under Consideration: Ice Shell Penetration

## Autonomous GN&C and Hazard Detection

**Pose estimation**

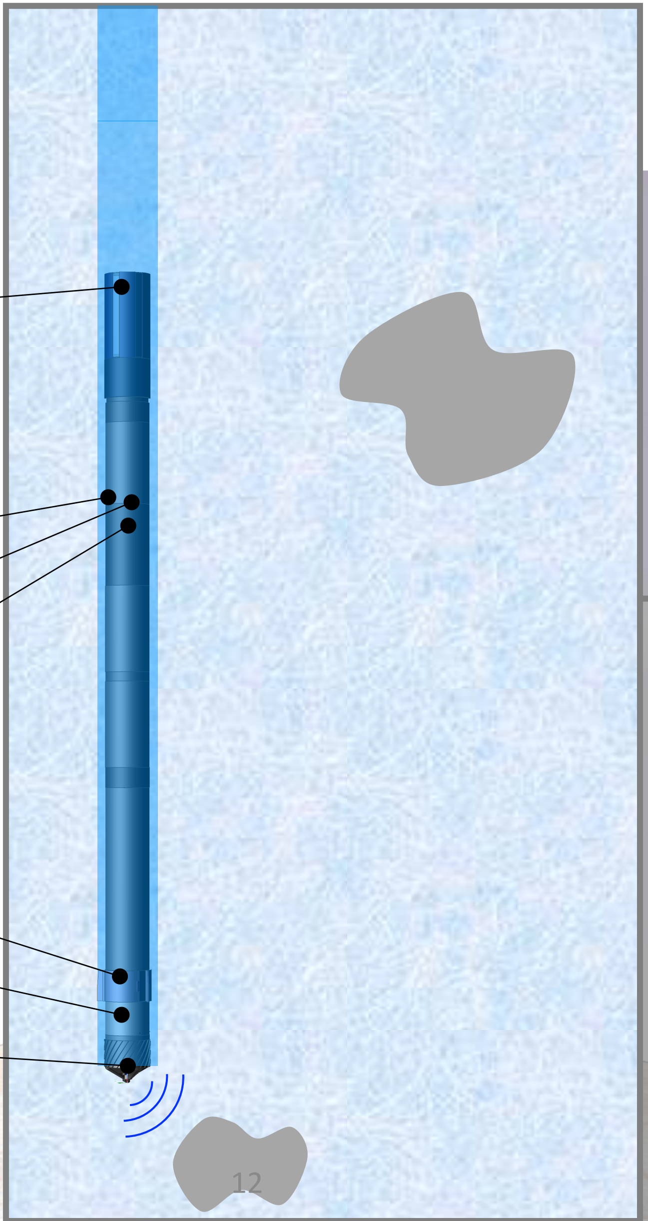
- Depth
- Lateral position
- Attitude

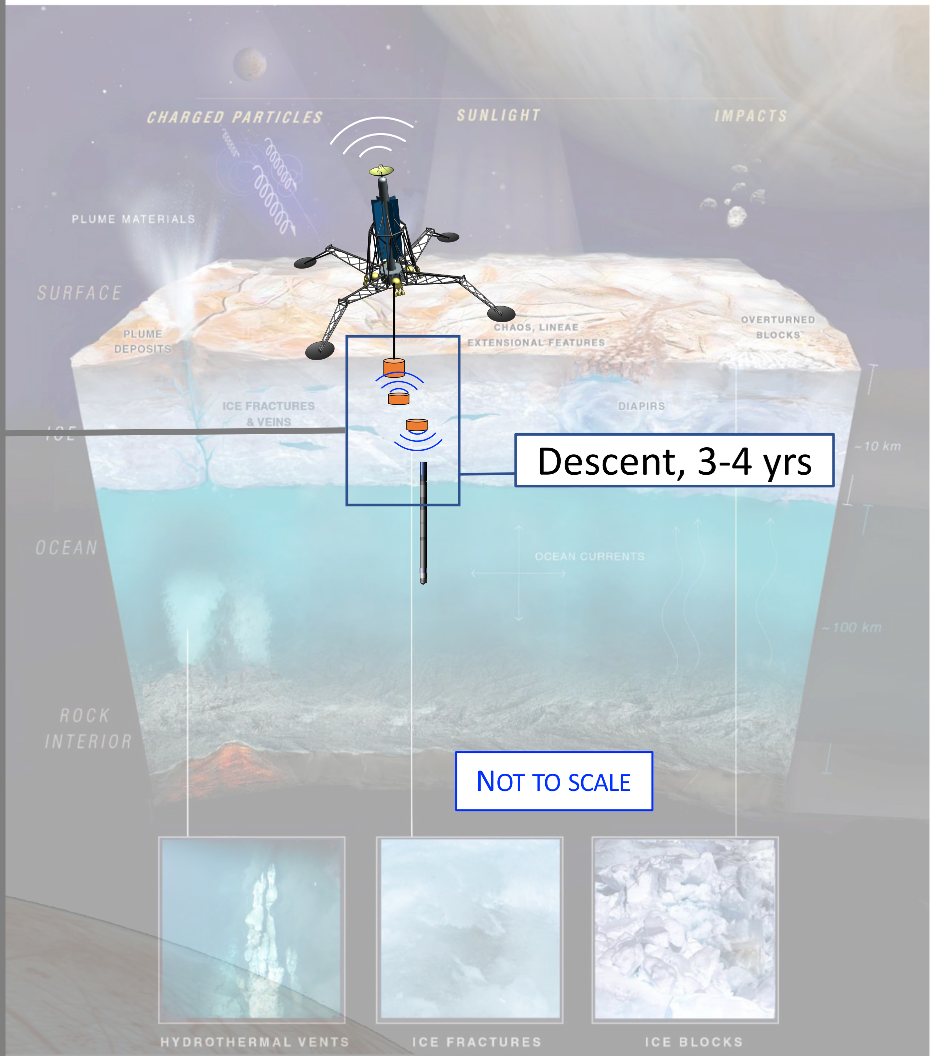
**Situational awareness**

- Mapping
- Hazard detection
- Ocean detection

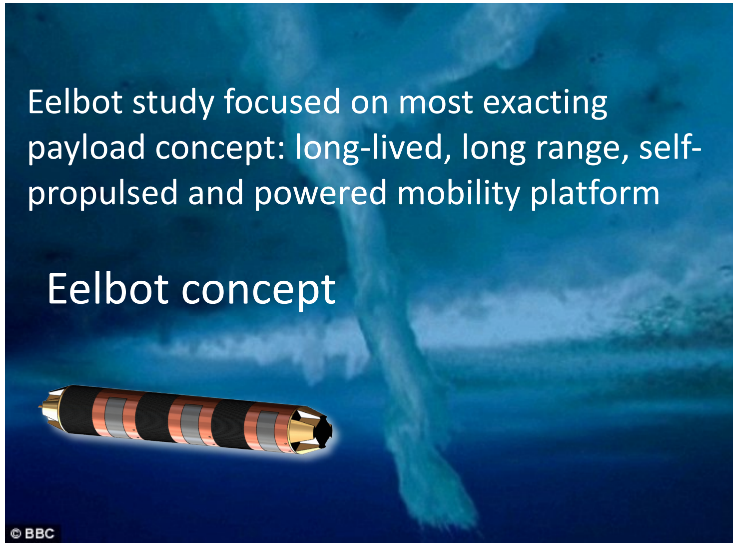
**Potential Sensors**

- Ranging from pucks
- Side-scan sonar, RF, imaging
- Inertial sensors
- Magnetometer
- Pressure sensors
- Thermocouples
- Forward sonar, RF, imaging

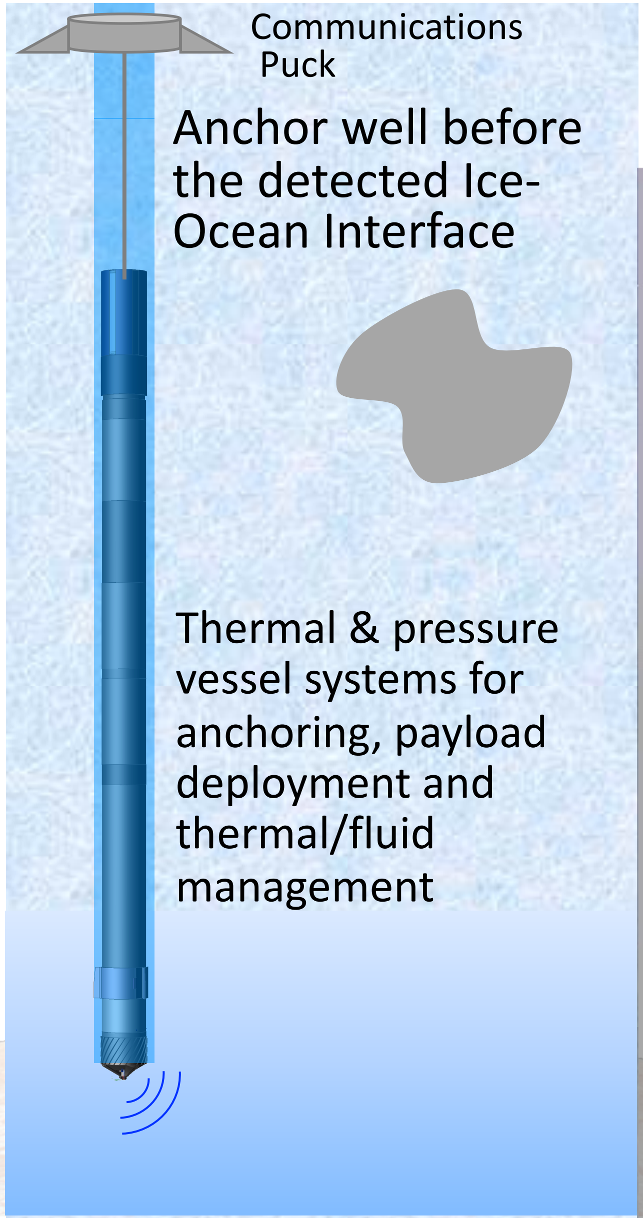


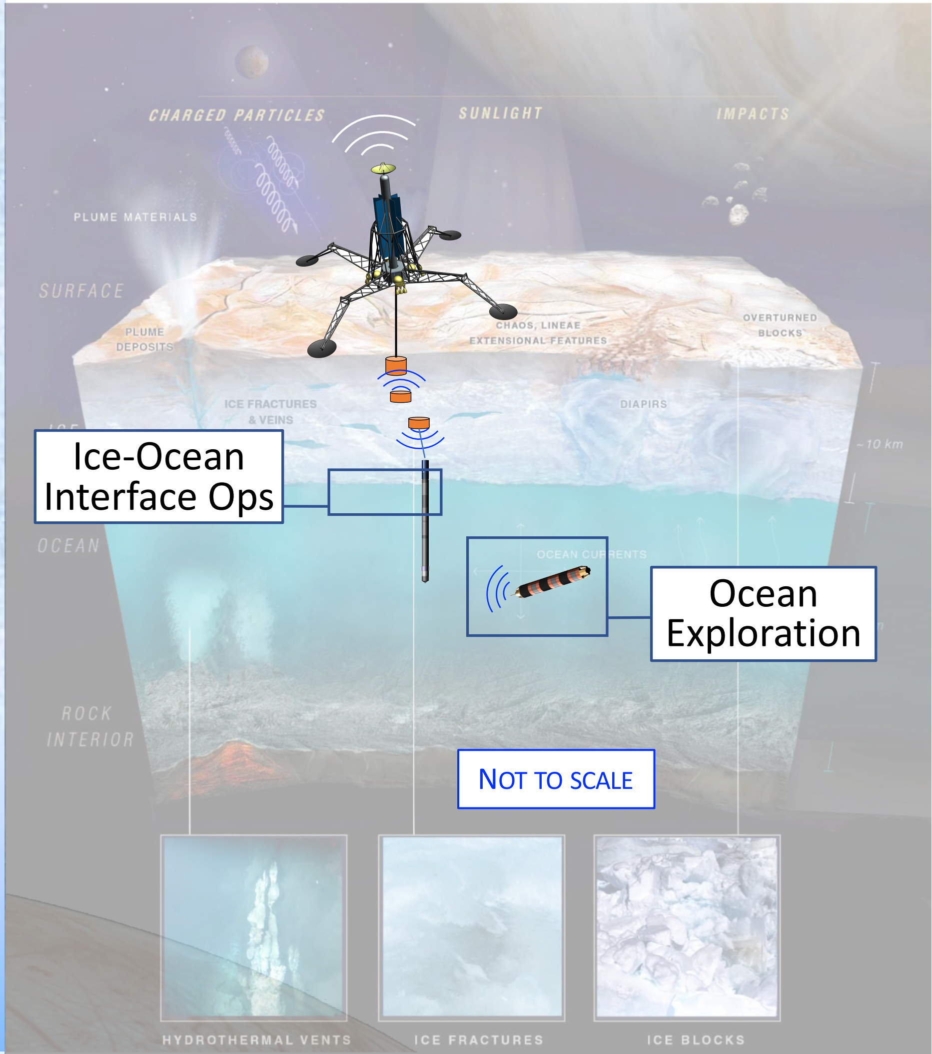


# Key Technologies Under Consideration: Ocean Exploration




- Deployment & operation of ocean explorer
- Miniaturized electronics and science instrument suite
- Highly autonomous operation
- Water propulsion
- On-board heat & power
- Ocean Exploration science may be tethered



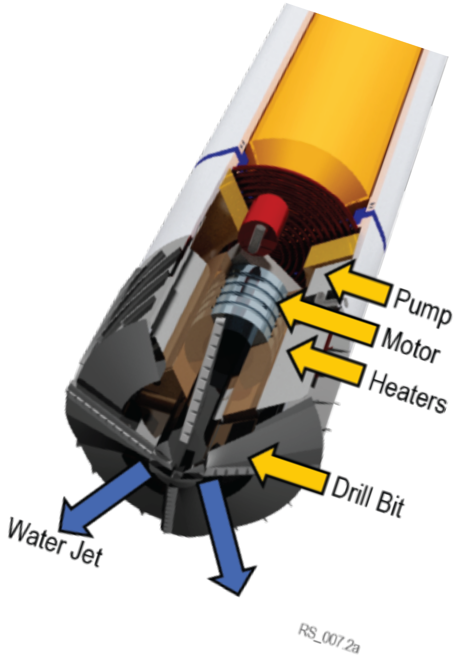
# Ice Shell Penetration: Notional Approach

Zimmerman, JPL 2001

## Melt Probe

- Thermal energy melts ice ahead and along probe
- Power can be aboard probe or transferred by tether from surface
- Rate of travel depends on:
  - Amount and distribution of thermal energy
  - Probe volume and form factor
  - Ice salinity

- Water Jets can be added to further melt ice and move melt water – electrical energy needed to drive pumps




Honeybee Robotics

## Mechanical Cutting

- Electrical energy drives blade to shave ice
- Chips need to be moved from front of probe

# Energy Source Options– Thermal and Electrical

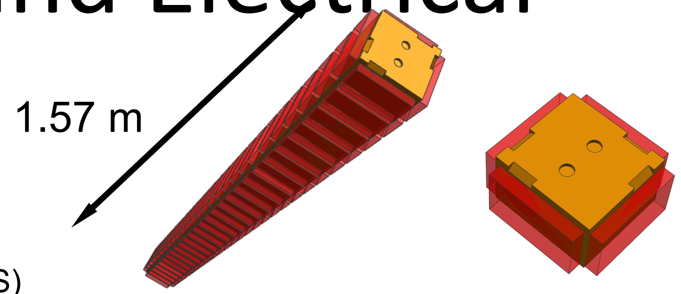
- Type
  - Nuclear
    - Fission Reactor
    - SRG (Stirling)
    - RTG (Thermo-Electric)
      - GPHS
      - Advanced Heat Source
  - Stored
    - Battery
    - Fuel Cell
    - Fly-wheel
  - Solar

Rationale: 9 year mission life necessitated active power generation

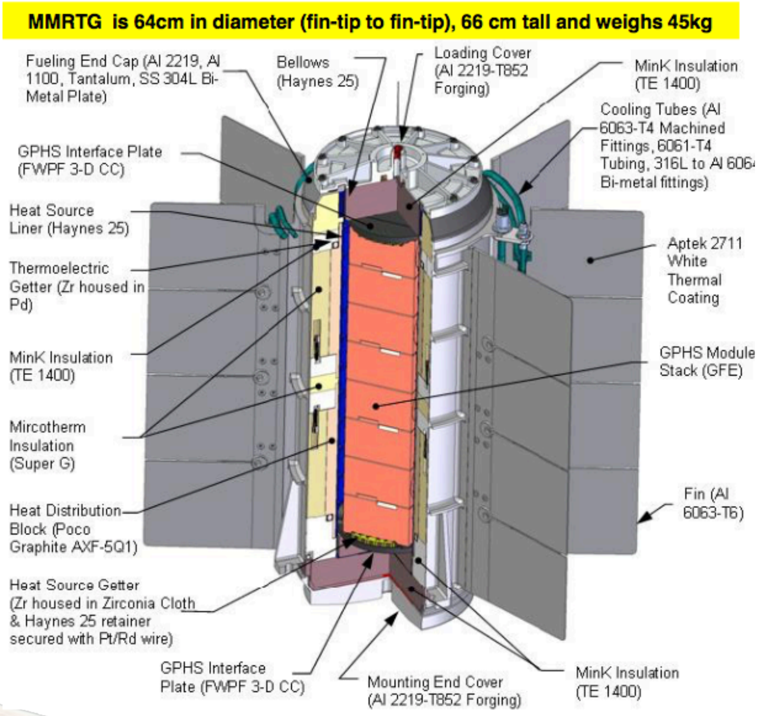
Rationale: Solar is deemed insufficient for zeroth order thermal energy needed to melt ice

General Purpose Heat Source (GPHS) Module

Rationale: Energy density and form factor are critical to ice penetration performance and meeting mission length constraints

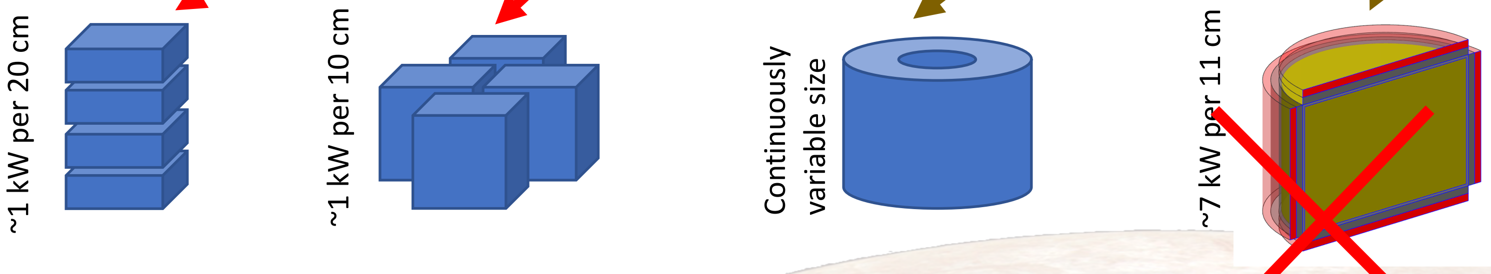



27 GPHS Blocks
6.75kW thermal



# Onboard Thermal & Electrical Power - Options Considered

| RTG Unit to be considered (each) | MMRTG | eMMRTG | Next Gen RTG | RTG Concept |
|---|---|---|---|---|
| Thermal Inventory, W | 2000 | 2000 | 4000 (modular) | 3000 |
| Electrical Power, launch, W | 110 | 145 | 400-500 (modular) | > 500 |
| Power, end of design life, W (17 years) | 55 | 91 | 308-385 | > 385 |
| Degradation rate, annual average | 4.8% | 2.5% | 1.9% | 1.9% |
| # GPHSs | 8 | 8 | 16 | Alternate: microspheres |
| Length, m | 0.69 | 0.69 | 1.04 | 0.3-0.6 |
| "Finless" housing diameter, cm | 29 | 29 | 20.5 [TBR] | > 20 [TBR] |
| Potential availability | "off-the-shelf" | QU by 2024 | QU by 2028 | Concept |




**A.** Single flat-stacked GPHSs

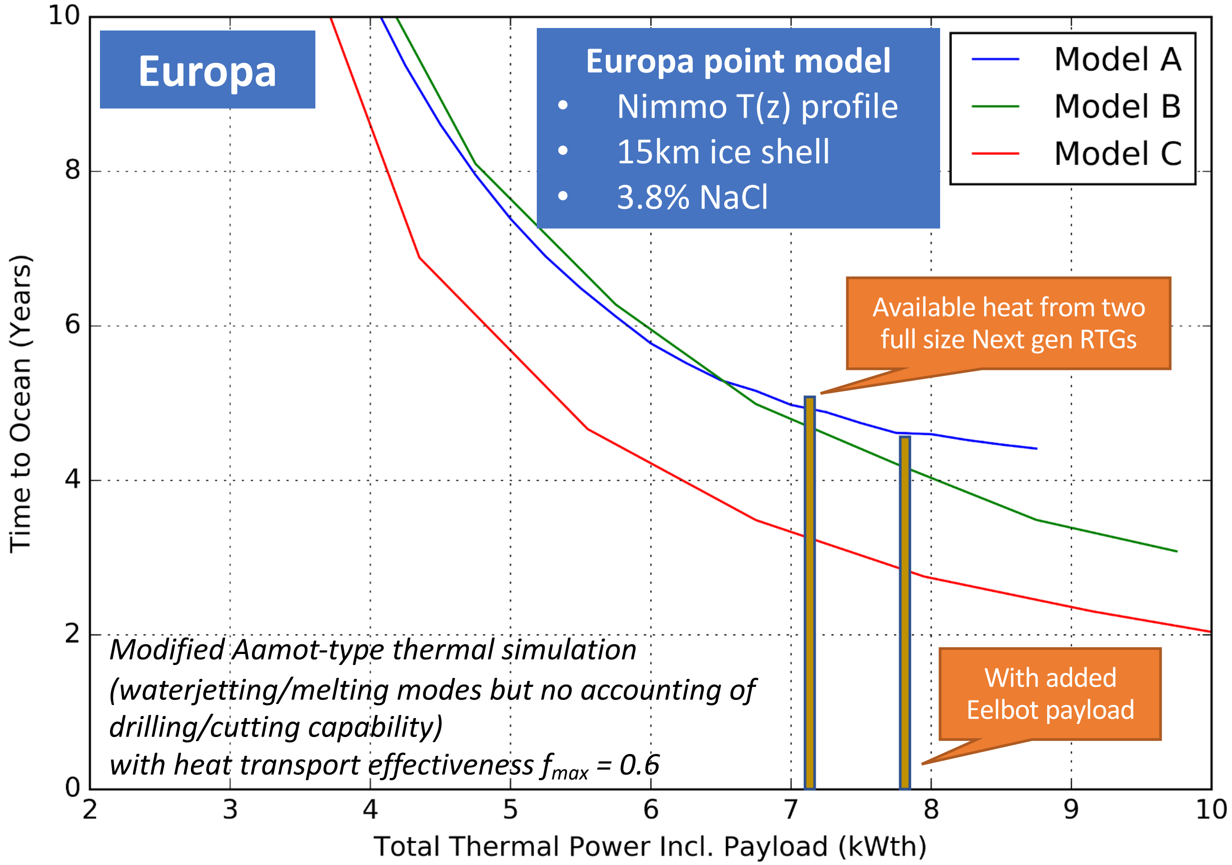
**B.** Quad edge-stacked GPHSs

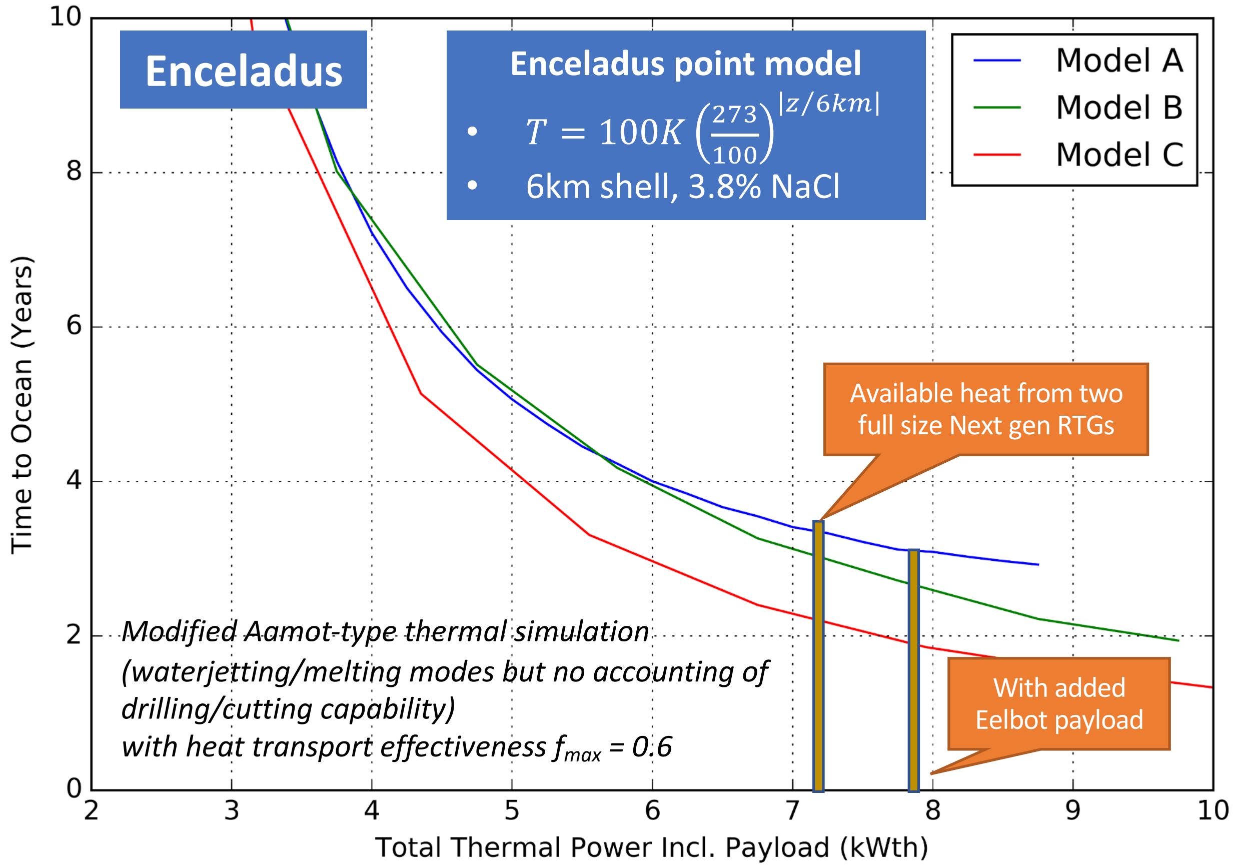
**C.** Annular packed microspheres

**D.** Compact packed microspheres

- Quad edge-stacked GPHS-based design is the most promising near term notional appraoch
- Microspheres-based heat source concept explored
  - This fuel form has been studied and some versions of this technology have been implemented in the past

# Performance modeling Studies: Europa & Enceladus

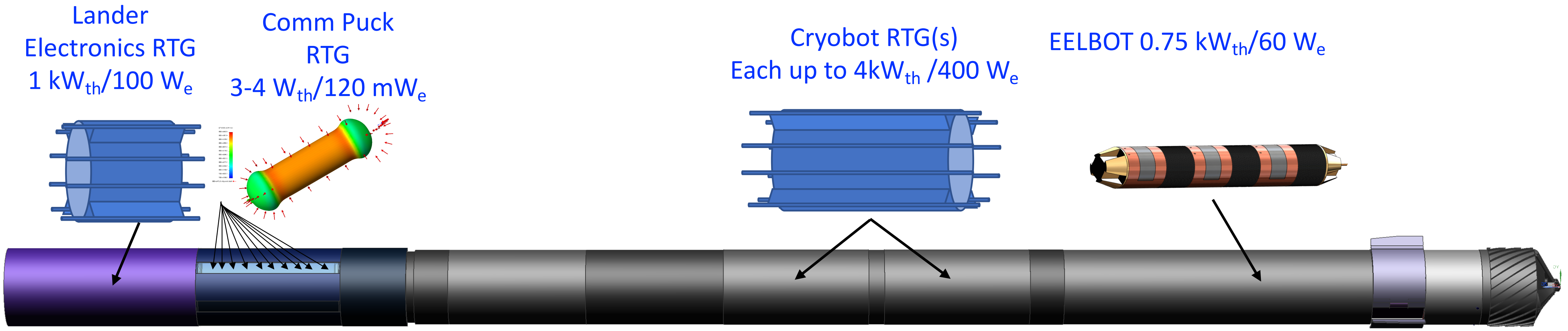


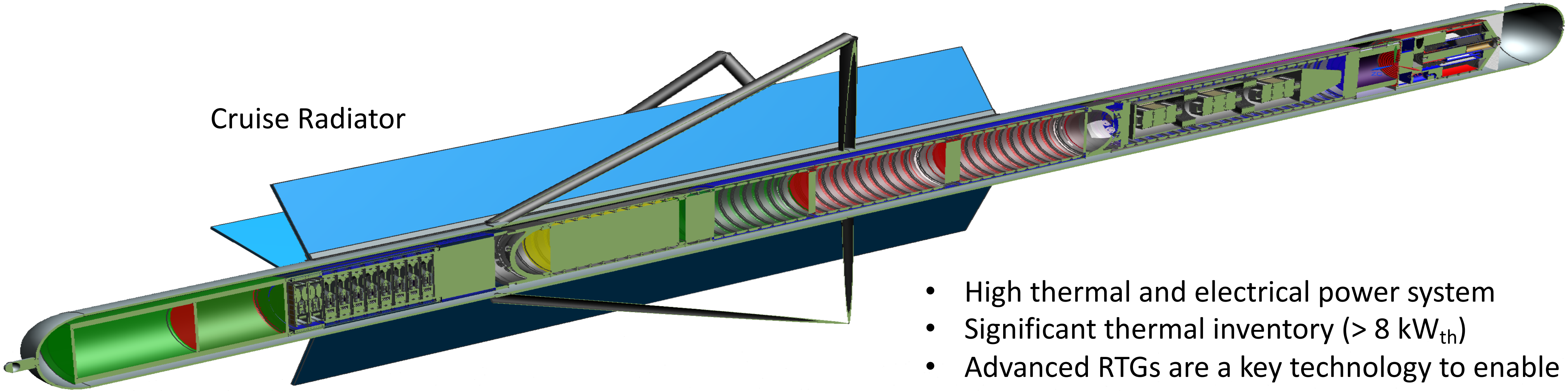




- Sweet spot at “6-8 kWth”, 1-2 year spread across 3 heat source models
- Probe diameter is a major driver for time-to-ocean performance
- Open trade: Heat inventory (RTG fuel) vs. time-to-ocean
- ~30% faster time to ocean for Enceladus partially offsets longer cruise phase

- One initial finding is that “melt plume” above descent probe may be several probe lengths
- Open: 1) impact of heated mechanical drilling/cutting on time-to-ocean, and 2) impact of large thermal inventory near ice/ocean interface

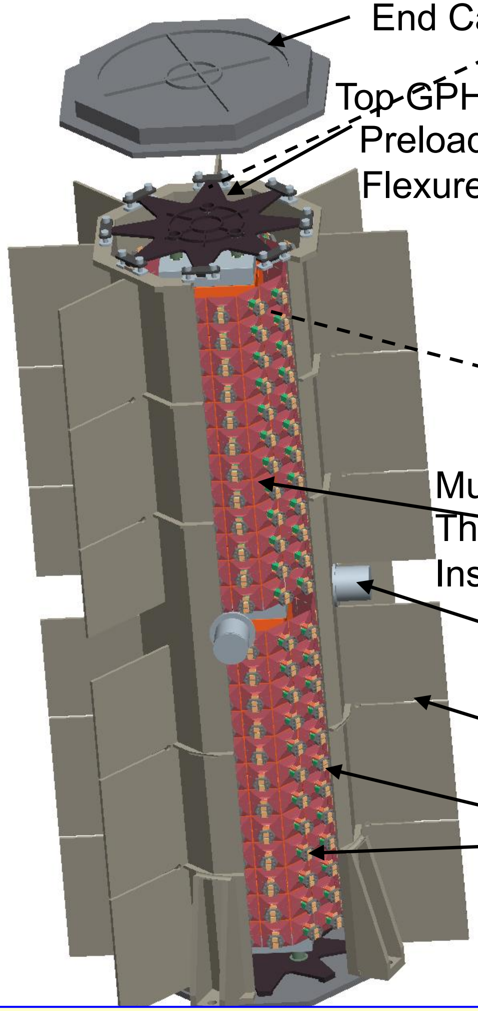
# Conceptual On-board Thermoelectric Power Systems



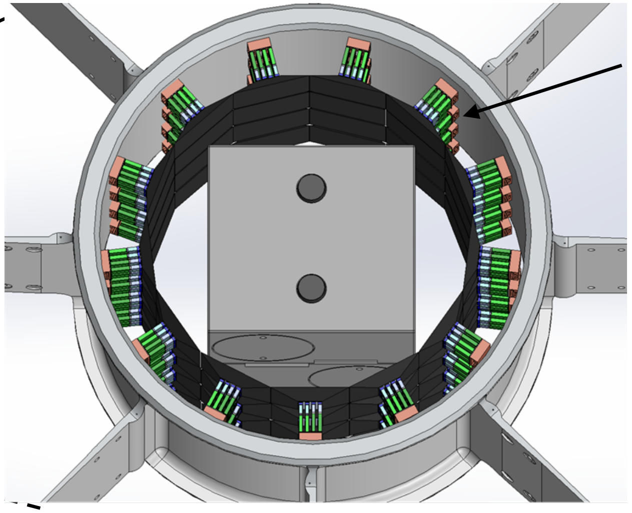




- High thermal and electrical power system
- Significant thermal inventory (> 8 kW$_{th}$)
- Advanced RTGs are a key technology to enable such mission concepts

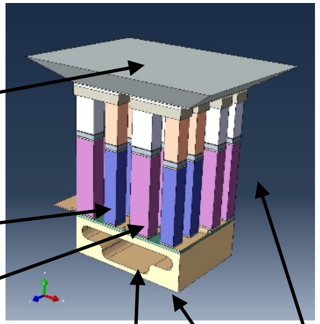
# Modular System & Thermoelectric Device Concepts for Notional Next Generation RTG

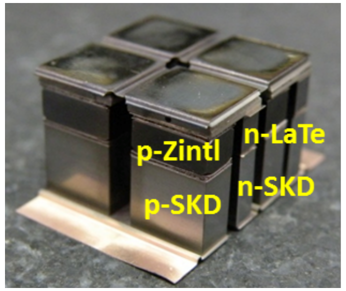



Potential Next Generation RTG conceptual design



52 TE 8-couple multicouples per 2-GPHS section



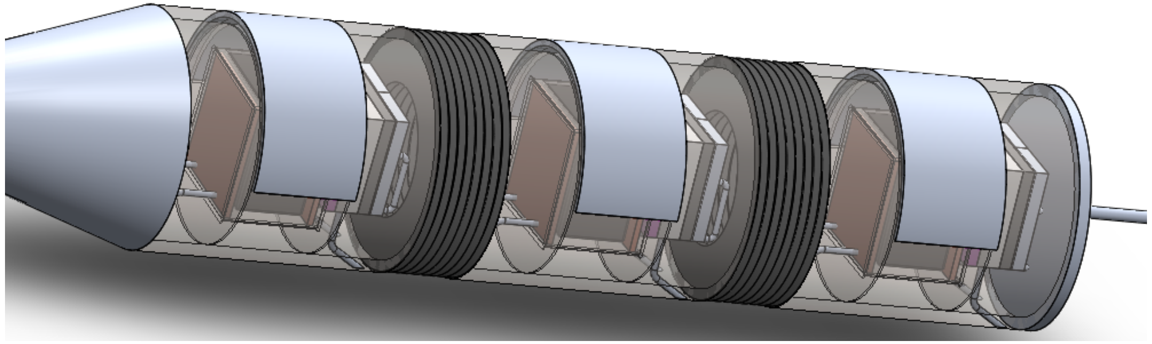




**Segmented Multicouple**
**Preliminary Design and proof-of-principle demonstration**

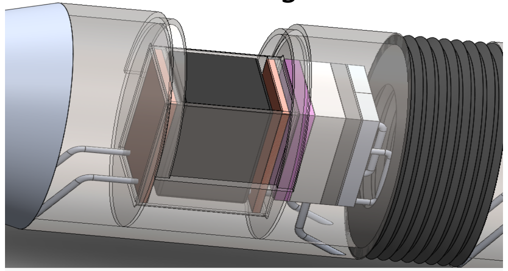
# EELBOT–Waste Heat-Powered Long-Life Ocean Explorer Study

<u>System architecture trades performed</u>

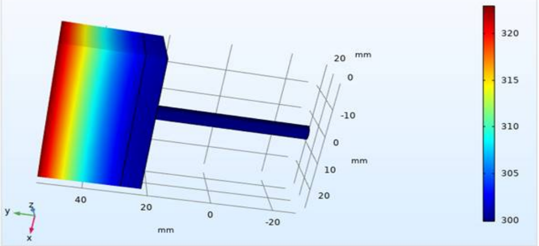
- Mobility/body type:
  - **Tethered for initial swim phase then untethered, powered, water-jet propulsion** OR permanently tethered, powered kite OR no ocean explorer
- Propulsion type:
  - **Direct waste heat-to-mechanical energy** OR waste heat-to-electrical-to mechanical energy
- Working fluid:
  - **Ocean water**/Internal water reservoir/Helium/Alkanes (butane, propane)/ Hydrofluorocarbons / chlorofluorocarbons
- Instrumentation distribution:
  - Single package OR **Distributed instruments** in individual segment



*Three-segment EELBOT design variant with “Mini-RTG” Concept*



*Segment design accommodating GPHS insertion against propulsion assembly*




*Time-dependent pressure/temperature COMSOL model of piston stroke*

<u>Potential system capabilities</u>

- Km-range mobility from initial ice/ocean interface entry point
  - Can perform swimming chemotaxis: follow a chemical “scent trail”
- Long-life operation provided by **radioisotope waste heat that is directly converted to mechanical energy** for water jet propulsion
  - Potentially multi-year undersea exploration
  - **Thermoelectric system** provides electric power for avionics / communication
- Carries suite of instruments for habitability, life detection
  - ChemSuite, multispectral cameras, temperature and pressure sensors, bio-signature/life detection

# Moving Forward

- Pursuing design studies and trade analyses
- Focus on developing high fidelity ice penetration models and verifying performance predicts
    - Collaborative work (JPL & external partners)
    - Summary of recent results to be presented next week at IEEE Aerospace Conference
- Refining cryobot designs and account for range of radioisotope-based thermal and electrical power system concepts
- Developing mission concepts of operations

Dare Mighty Things