2018 Conference on Advanced Power Systems for Deep Space Exploration

Sub-Surface RTG Systems and New Heat Sources

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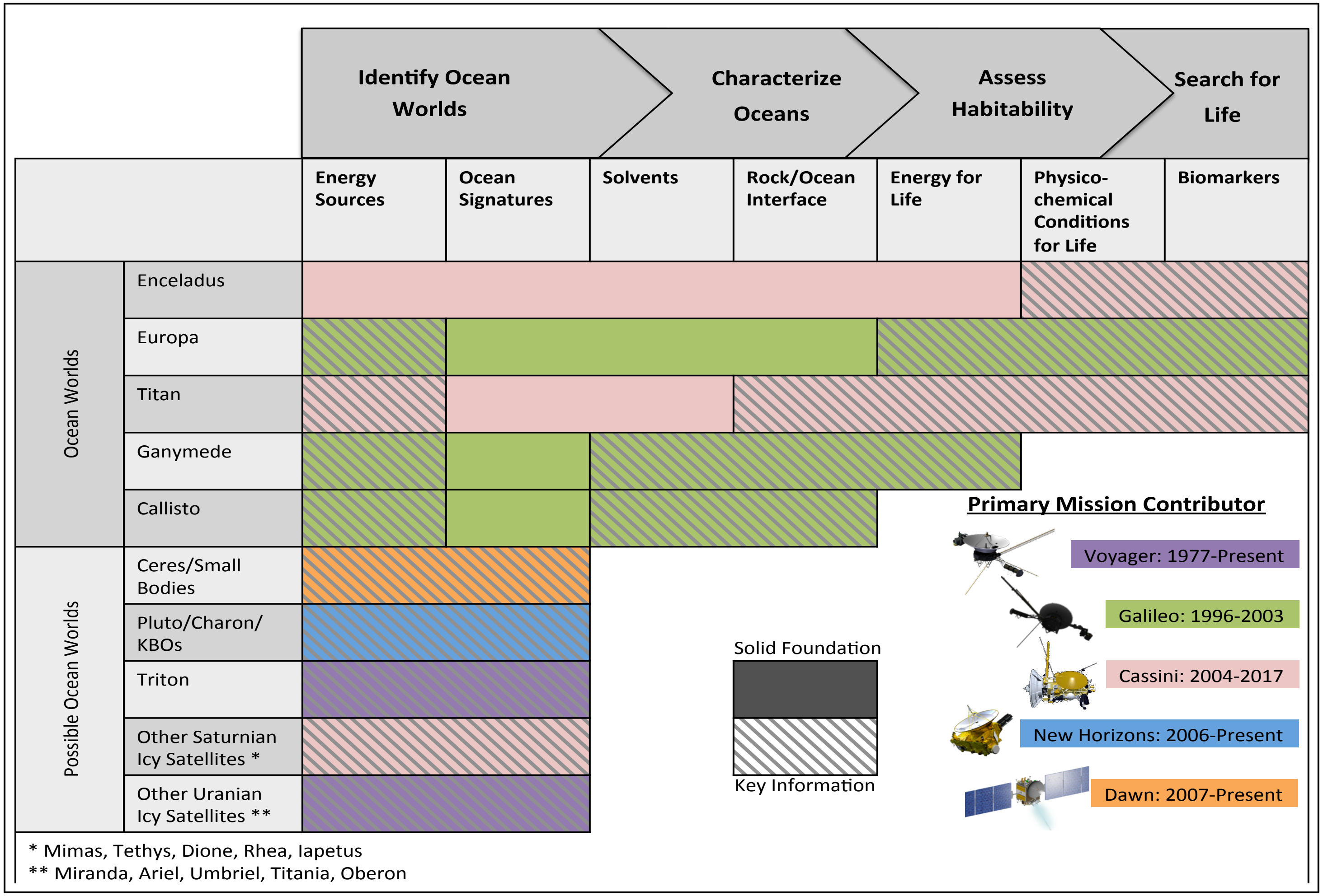
AGENDA

- Proposed Future Deep Space Icy/Ocean Worlds Targets
- Current / Heritage Power Systems
- Design Investigations into Future Sub-Surface Ice Penetration, RTG Systems, and Heat Sources
  - Ice Penetration Challenges
  - Ice Penetration Solutions and Performance Characteristics
- Summary

Where do we need to go?!

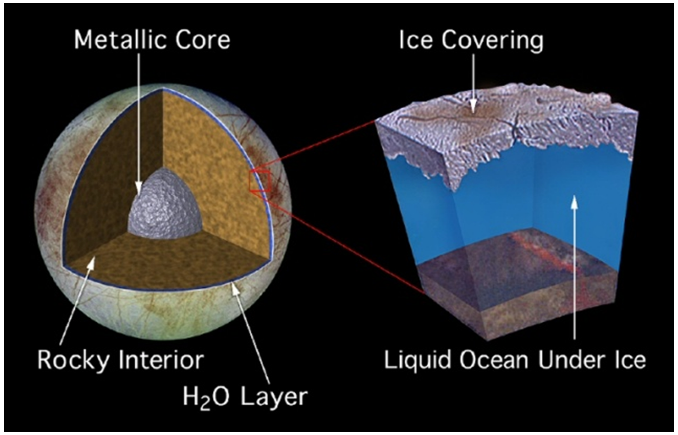


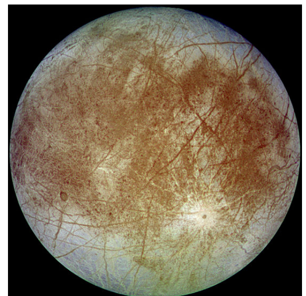
Spacecraft have been gathering data to define Ocean Worlds since 1977, starting with the Voyagers. Today we have solid information to define key Ocean World parameters for Enceladus (Cassini), Europa (Galileo), Titan (Cassini), and Ganymede and Callisto (both Galileo). Of these Enceladus, Europa, and Titan seem to stand out as the Ocean Worlds with most promise in the search for life elsewhere in the solar system.

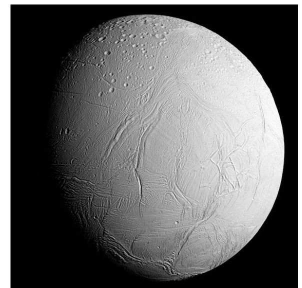
Ref: Hendrix, A. and T. Hurford. February 2017. Roadmaps to Ocean Worlds: OPAG Update. Atlanta, GA.

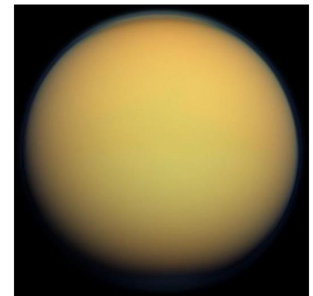
Where do we need to go?!

Europa Internal Structure









	Europa	Enceladus	Titan
Landed Mass (tons)	Atlas V: 1400; DeltaIVh: 2400; SLS: 4100 tons	Atlas V: 2750; DeltaIVh: 4800; SLS: 10500 tons	Atlas V: 2000; DeltaIVh: 3500; SLS: 8000 tons
Ice Thickness (km)	10-30 km	5-40	100
Ocean Depth (under ice) (km)	110	30	200
Radius (km)	1560	252	2575
Gravity (m/sec^2)	1.31	0.11	1.35
Planetary System	Jupiter	Saturn	Saturn

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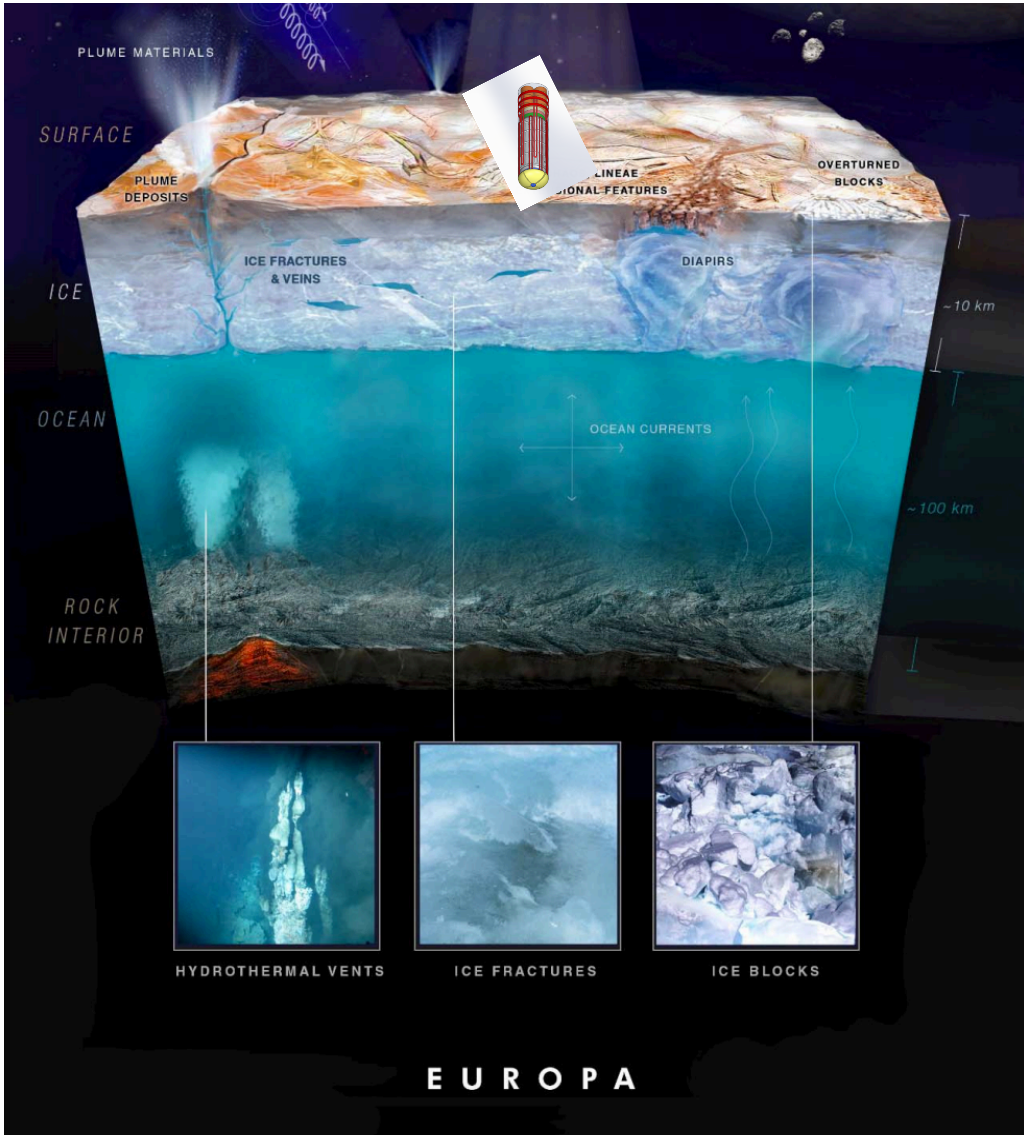
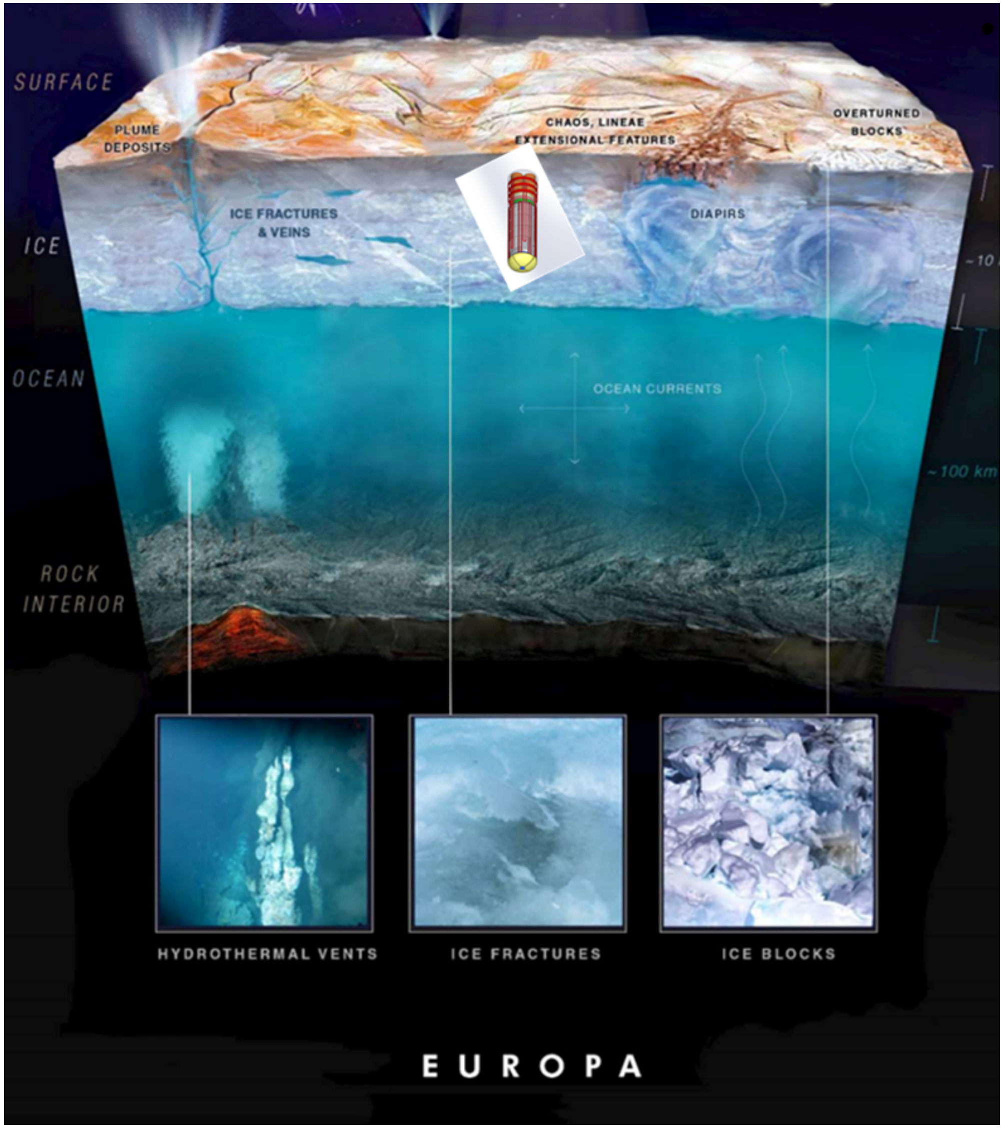
Stages of Ice Penetration



Initial Near-Surface Stage

- First 1-5 meters
- Vacuum Conditions
- Governed by Sublimation & Vacuum Conditions
- Extreme Ice Environment Conditions
    - Very Hard Ice
    - Very Cold Ice (~100 K)
    - High Thermal Conductivity
    - Ice Structure is Issue
    - Ice Salinity (~3.8%)
- Exact Ice Conditions Uncertain
- Probe Orientation is critical
- The portion likely will require mechanical drilling to start process

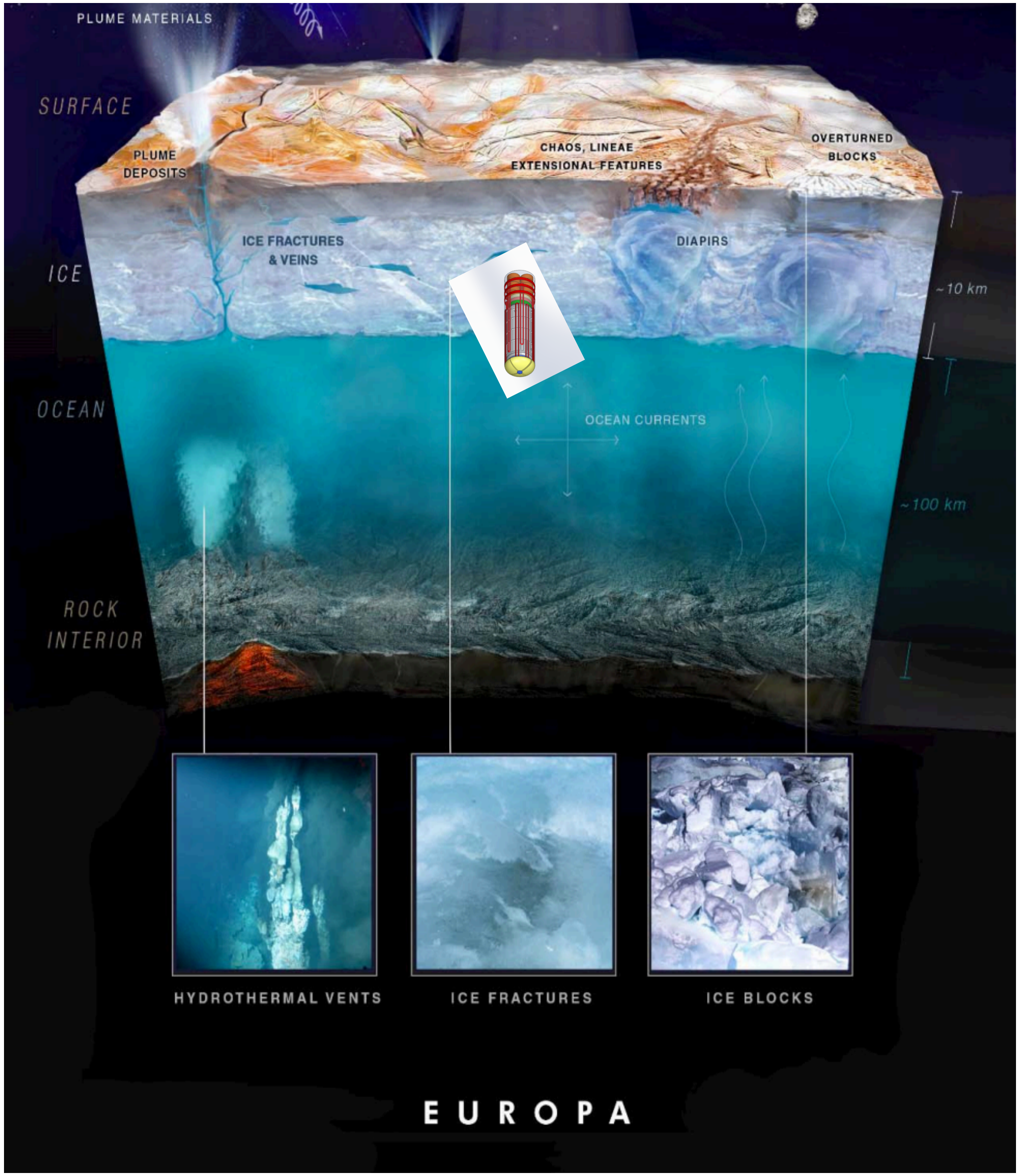
Stages of Ice Penetration



In-Ice Traversing Stage (0.1-5 km)

- Probe covered/surrounded by ice
- Extreme Ice Environment Conditions
  - Still Cold Ice but Warms up (~100-160 K)
  - High Thermal Conductivity
  - Ice Structure
  - High Pressure
  - Ice Salinity (~3.8%)
  - Ice contamination (dirt, rocks, “voids”)
- Exact Ice Conditions Uncertain
- Design governed by complex thermal / fluid systems for probe thermal management and descent
- This portion will require water jetting along with melting to increase penetration speed
- Liquid movement from probe front to rear
- High pressure vessel required
- Probe maneuvering and steering a serious concern
- Communication with surface – communication transceivers

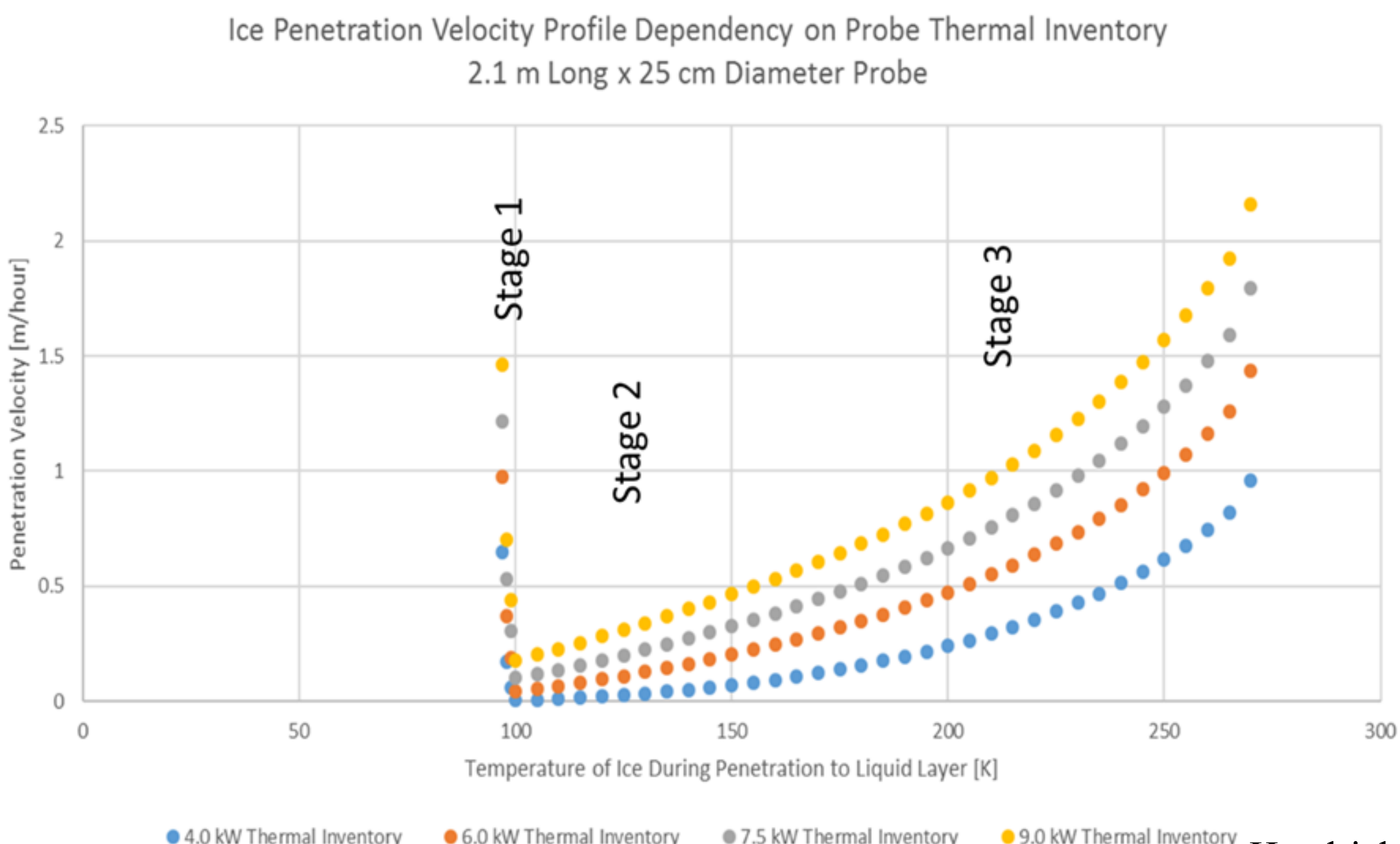
Stages of Ice Penetration



- **Ice – Ocean Interface Stage (10-20 km)**
  - Probe approach ice-ocean interface
  - Ice Environment Conditions
    - Warmer Ductile Ice (~230-273 K)
    - Ice Structure could be slushy near water
    - High Pressure
    - Ice Salinity (~3.8%)
  - Design governed by complex thermal / fluid systems for probe thermal management and descent
  - This portion will likely only require melting
  - Liquid movement from probe front to rear
  - High pressure vessel required
  - Probe maneuvering and Slowing Down and potential attachment to ice
  - Communication with surface – communication transceivers

Ice Penetration Velocity Profiles-Melting Only

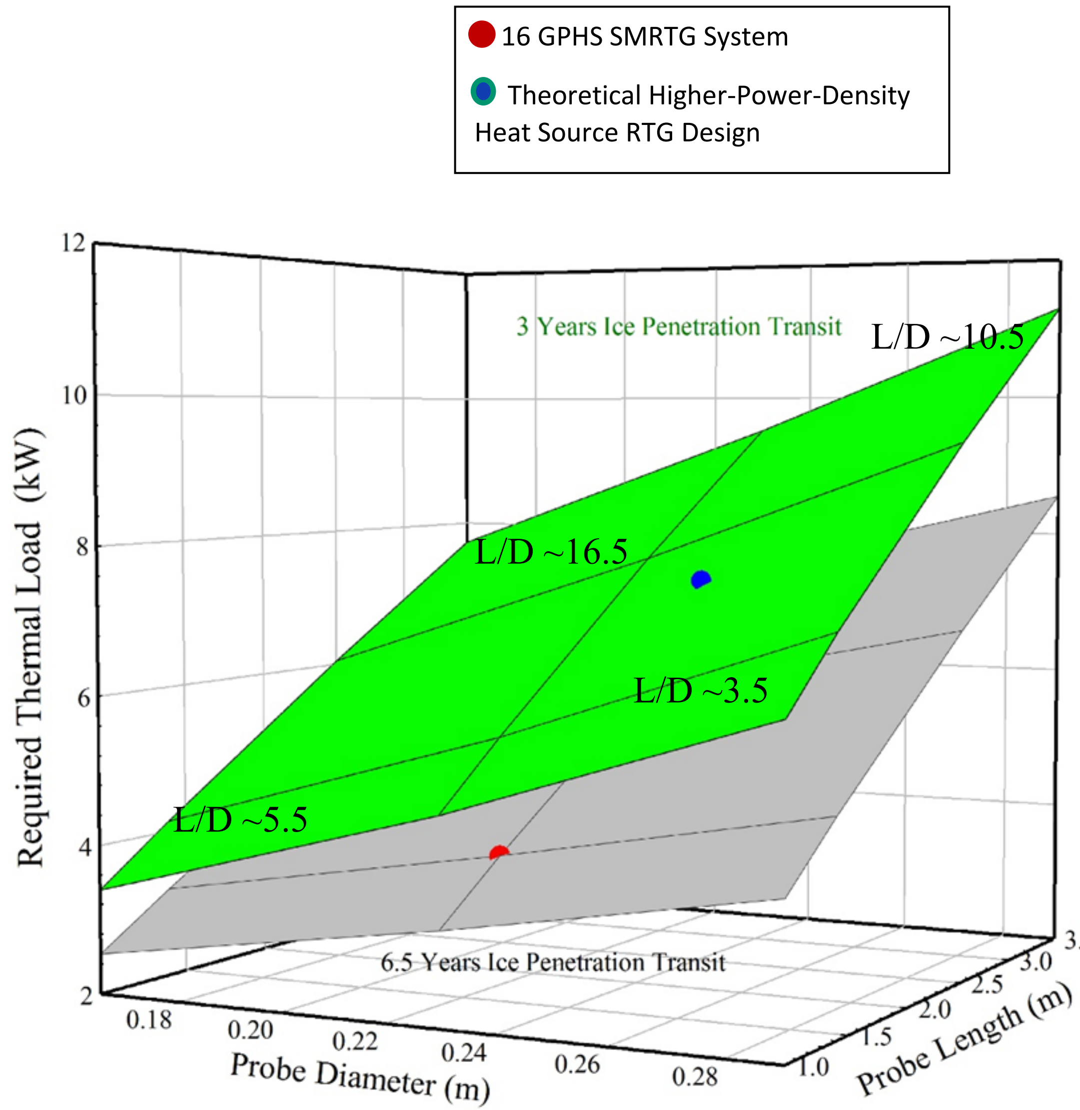
- Early Scoping Projections
- Enormously complex thermal / fluid dynamic challenge
- Driven by ice environment and thermophysical/structural properties
- Governed by Available Thermal "Inventory" in CryoProbe



Hendricks, 2017

Required Thermal Source Impact on CryoProbe Design

- Provides the complete picture on probe dimension impacts
- Shows what 16 GPHS system can do
- Severe mission time impact
- Latest detailed thermal/fluid models are showing ~8.5 kW is necessary @ 160 K
- Much higher than less-detailed models suggest
- L/D is critical design parameter and drives required thermal load

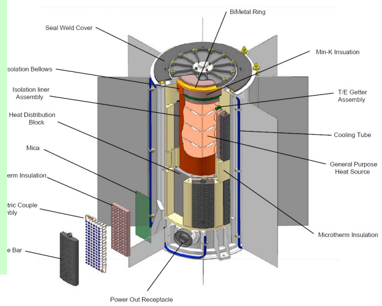


Hendricks, 2017

Available Heat Sources and Power Levels for Current and Future Concept Radioisotope Thermoelectric Generators

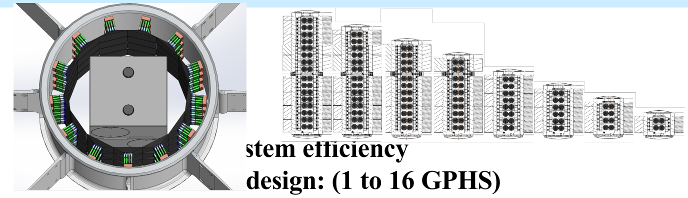
MMRTG
Flight Qualified
(on MSL, baselined for Mars 2020)

eMMRTG
Technology Maturation
(~ 2024 target for system availability)



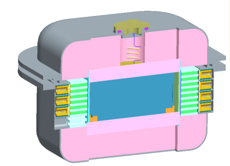
~ 120 to 160 W_e, 6.3% to 8% eff., 44 kg
~ 1880 W_{th} at 450 K T_{rej}

Segmented Modular RTGs Concepts
Technology Advancement
(~ 2029 target for system availability)



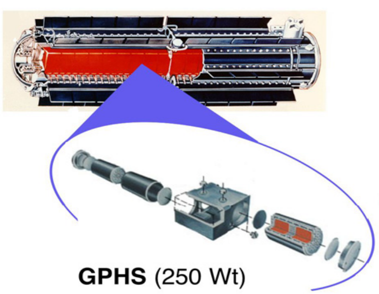
stem efficiency
design: (1 to 16 GPHS)
~ 23 to 460 W_e ; ~ up to 8.6 W/kg
~ 500 K T_{rej}

1-GPHS Small RTG Concept

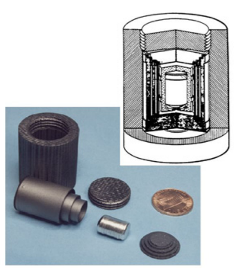


~ 20 to 50 W_e, 6-10 kg
~ 230 to 150 W_{th} at 400-350 K T_{rej}

Existing Flight Qualified Heat Sources

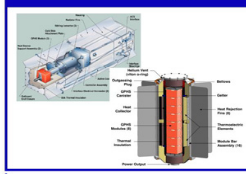


GPHS (250 Wt)

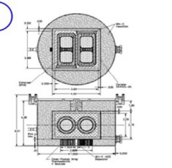


RHU (1 Wt)

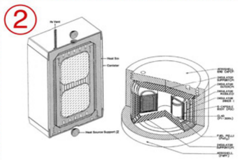
Application Power Levels



>100 Watts
- Under development – MMRTG & SRG
- >110 We & 35-40 kg per unit
- 2-8 GPHS per unit
- **Available by 2008-2009**

① 

10 to 20 Watts
- Preliminary concept studies only
- 1 GPHS per unit
- Can use existing thermoelectric technology
- Requires systems engineering development

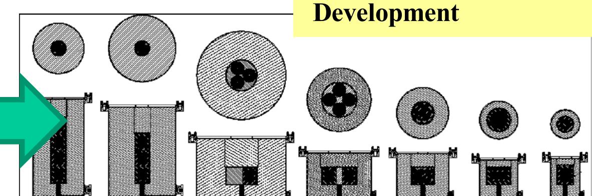
② 

0.1 to < 10 Watts
- Some concept studies from early 1990's
- Fractional GPHS or assembly of RHUs
- Requires **redesigned thermal source aeroshell** and systems engineering development
- **More extensive development than options 1 or 3**

③ 

≥ 0.01 Watts
- Concept studies and technology development (Hi-Z)
- ≥1 RHU thermal source per unit
- Requires systems engineering development

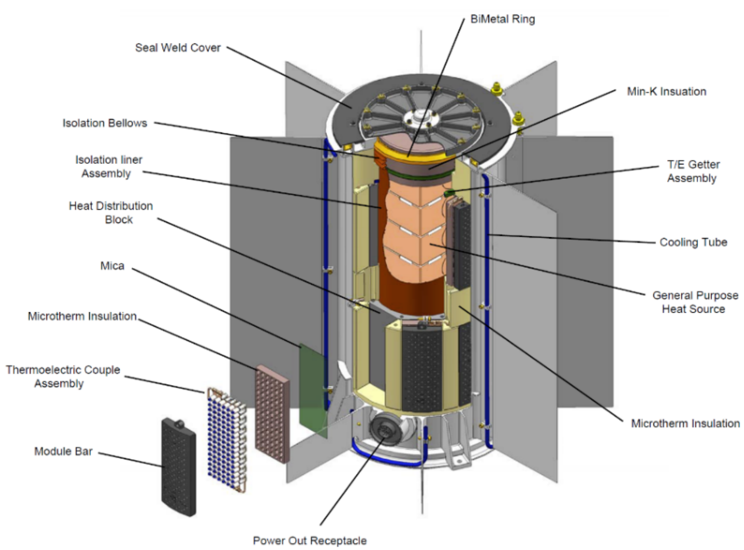
mW-RTG RHU-Based Concepts - Limited Development



- 1.1 W_{th} per RHU
- 4% efficient for 500 to 300 K operation
- ~ 45 mW_e/RHU
- But could be 6-10% efficient between 300 and 100 K (Carnot!)

State-of-Practice: Heritage and Current RTGs

Heritage system not available anymore



Current "off-the-shelf" Multi-Mission RTG

- GPHS-RTG (Galileo, Ulysses, Cassini, New Horizons)
  - **Vacuum-only operation**
  - TE materials: n-type and p-type Si-Ge alloys
  - Heat source: ~ 4500 Wth (18 GPHS)
  - Beginning of life (BOL) power: ~ 295 W_e
  - BOL specific power: ~ 5.1 W/kg
  - Annual power loss ~ 1.86% (exp. rate) - Cassini
- MMRTG (MSL, Mars 2020)
  - Developed to **"Multi-Mission" specifications**
  - TE materials: n-type PbTe and p-type TAGS/(Pb,Sn)Te
  - Heat source: ~ 2000 Wth (8 GPHS)
  - Beginning of life (BOL) power: ~ 122 W_e
  - BOL Specific power: ~ 2.8 W/kg
  - Annual power loss ~ 4.8% (exp. rate) - MSL

➢ ***Heritage/Current Systems use GPHS (Step 1 and Step 2) Designs for Thermal Sources***

➢ *Very Adequate for Current and Heritage GPHS-RTG and MMRTG Power Systems*

The need for Integrating RTGs with Pressure Vessels

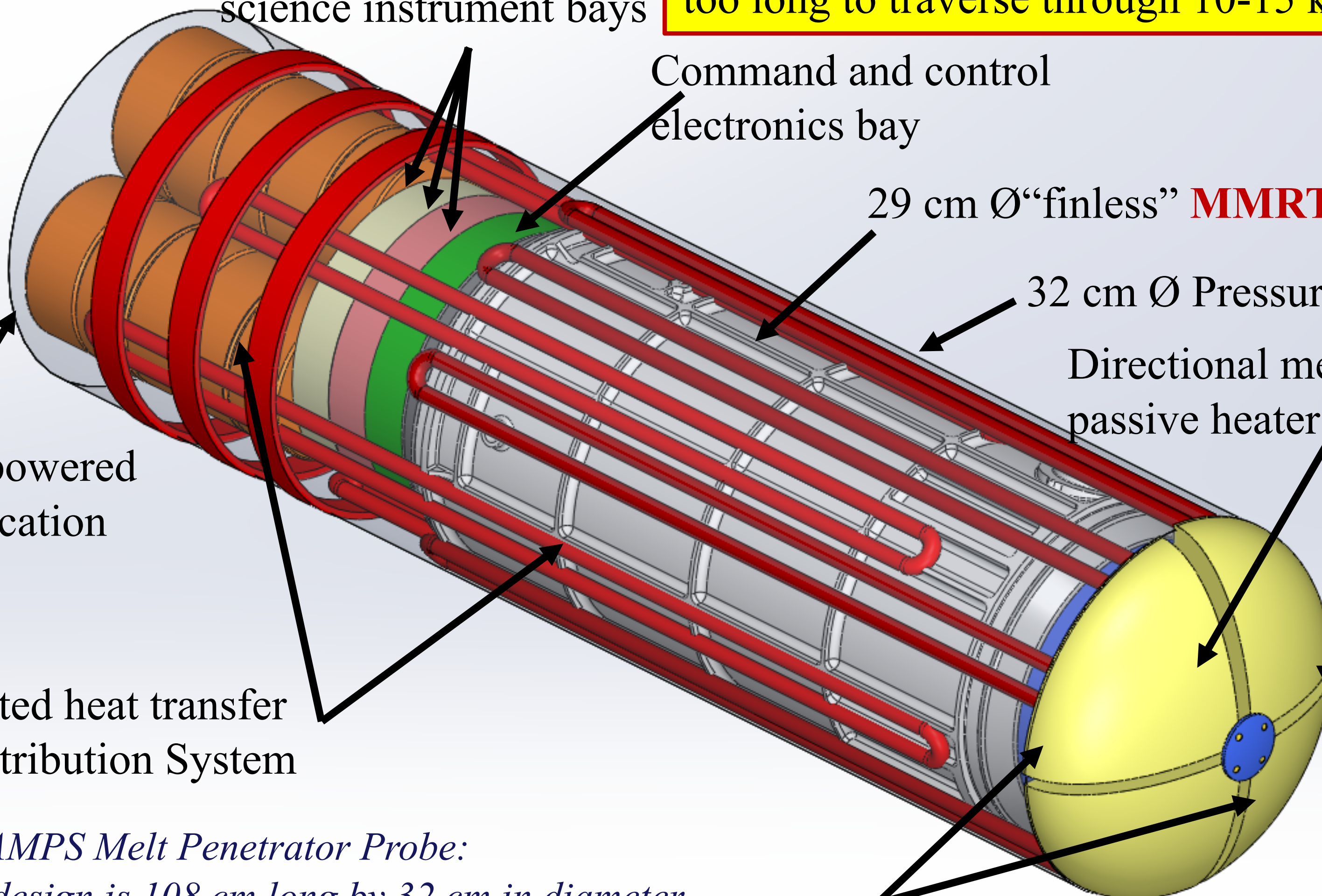
- Pressure vessels are required due to very high pressures encountered in the ice sheets of Ocean Worlds and others in the table below.
- The waste heat of an RTG provides advantage to a melt probe; other technologies require the conversion of electricity back into waste heat to be distributed throughout a melt probe's surface and interior for housekeeping and melting.

	composition	g (m/s2)	h max (km)	fluid density (kg/m3)	P max (atm)	shell thick Al (cm)	shell mass Al (kg)
Earth	H2O	9.8	11	1000	1064	4.31	202
Ganymede	H2O	1.43	144	1000	2032	5.64	275
Callisto	H2O	1.24	150	1000	1836	5.40	261
Europa	H2O	1.31	30	1000	388	2.90	130
Mimas*	H2O	0.064	100	1000	63	1.49	64
Enceladus	H2O	0.133	40	1000	53	1.39	59
Titan - Lakes	C2H6	1.352	0.3	650	3	0.49	20
Titan - Subsurface Ocean	H2O	1.352	20	1000	267	2.52	111
Triton	H2O/NH3	0.779	200	1000	1538	5.02	240
Ceres*	H2O/NH3	0.28	?	?		0.00	0
Pluto	H2O/NH3	0.62	260	1000	1591	5.09	244

This is a preliminary analysis. The numbers will change with further study. The points are: the need for a pressure vessel and demand for waste heat are significant.

RTG-Powered Cryo-Hydro Autonomous Melt Probe System Concept

Issue with this design is mission times are too long to traverse through 10-15 km of ice



Envisioned CHAMPS Melt Penetrator Probe:

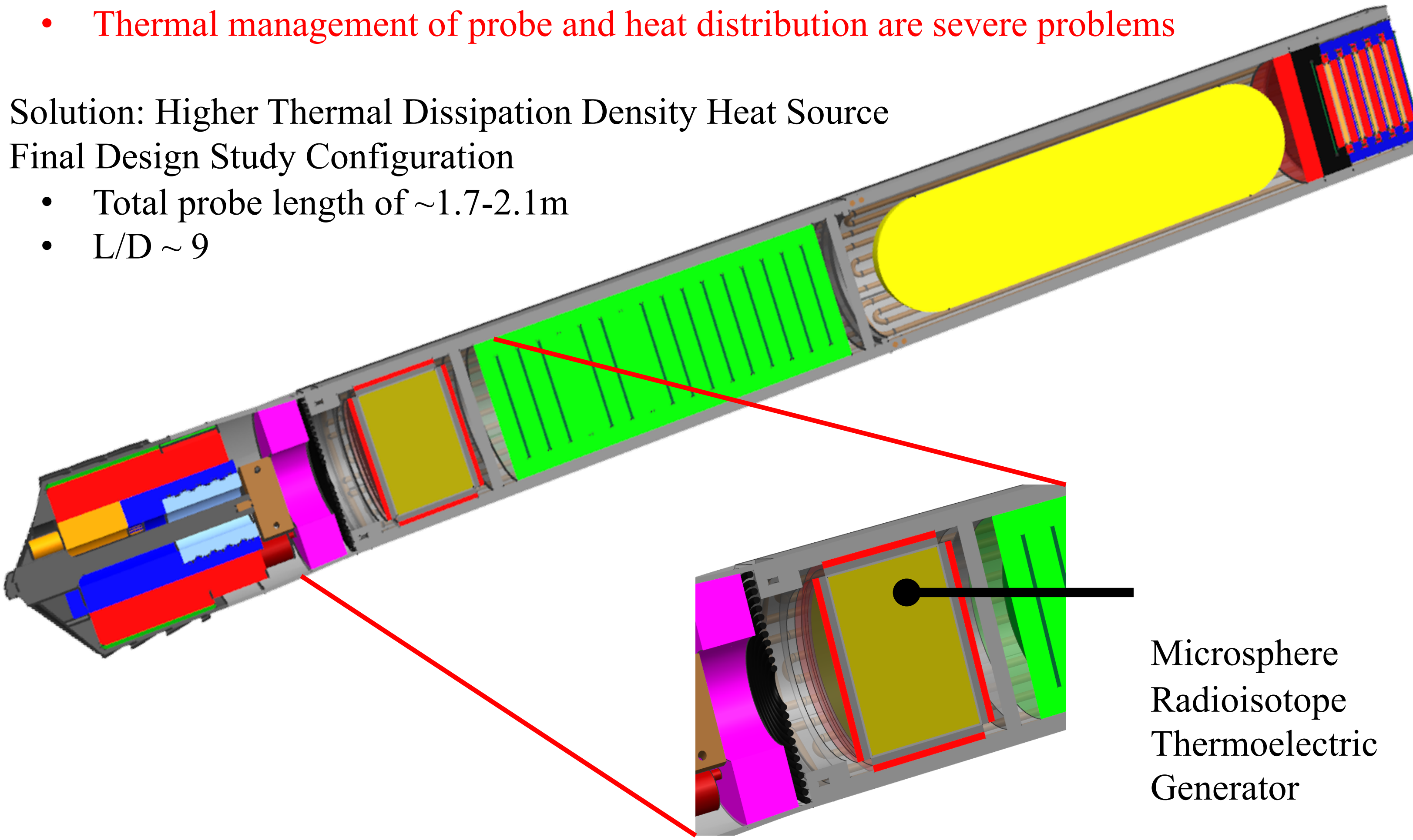
- *Conceptual design is 108 cm long by 32 cm in diameter*
- *Finless MMRTG within pressure vessel*
- *Includes 15 discrete ice transceiver "pucks" self-powered thanks to a 3-RHU mW-RTG delivering more than 100 mW*

24 October 2018

Latest CryoProbe Design Using Advanced Heat Source Concept

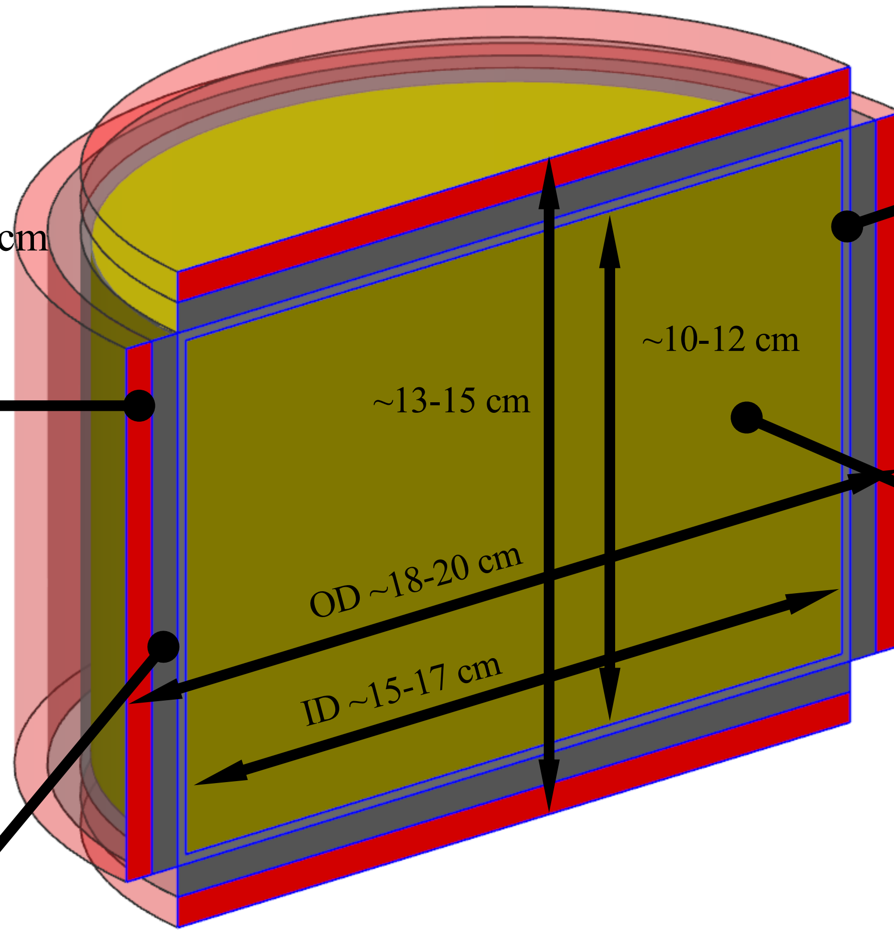
- GPHS-based designs lead to probe lengths that can be too long (~4 m) or wide (>28 cm)
  - Melting rate drops & risk of freezing in place increases dramatically
  - Thermal management of probe and heat distribution are severe problems

- Solution: Higher Thermal Dissipation Density Heat Source
- Final Design Study Configuration
  - Total probe length of ~1.7-2.1m
  - L/D ~ 9



Advanced High Thermal Density Heat Source Concept

- This configuration provides 7-7.5kW thermal
- 2.7 – 3.2 W_{th} / cc
- Equivalent to stack of 28 GPHS modules that is 163cm X 9.96cm X 9.32cm
- GPHS: 0.46 W_{th} / cc



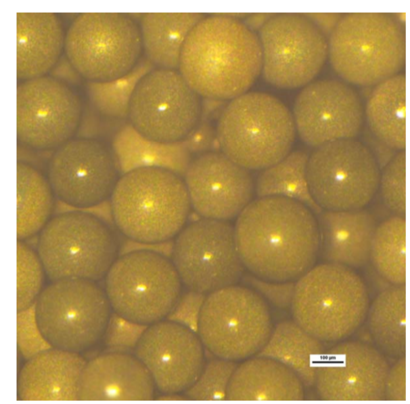
Three-segment Thermoelectric Converters:
2X ZINTL, 1X BiSbTe
T_{hot} ~1000 C, T_{cold} ~ 50 C,
η_{TE} ~ 15 %

Thermal Conducting Graphite Fibers (Also provides structural support)

7.24mm Fine-Weave Pierced Fabric, All Around (GPHS Aeroshell Heritage)

Dual Size Plutonium Dioxide Microspheres (60-70% Fill Factor), Individually Encapsulated

~250 um diameter microspheres



Pre-decisional information for planning and discussion only.

Ice Penetration Probe Designs
Thermal Modeling Introduction

Model description

- CFD Analysis of passive (purely conductive) and active heating (waterjets) required to design heat distribution and probe thermal management
- Software used: Star CCM +
- Multiphase Model –H2O
- Laminar Flow

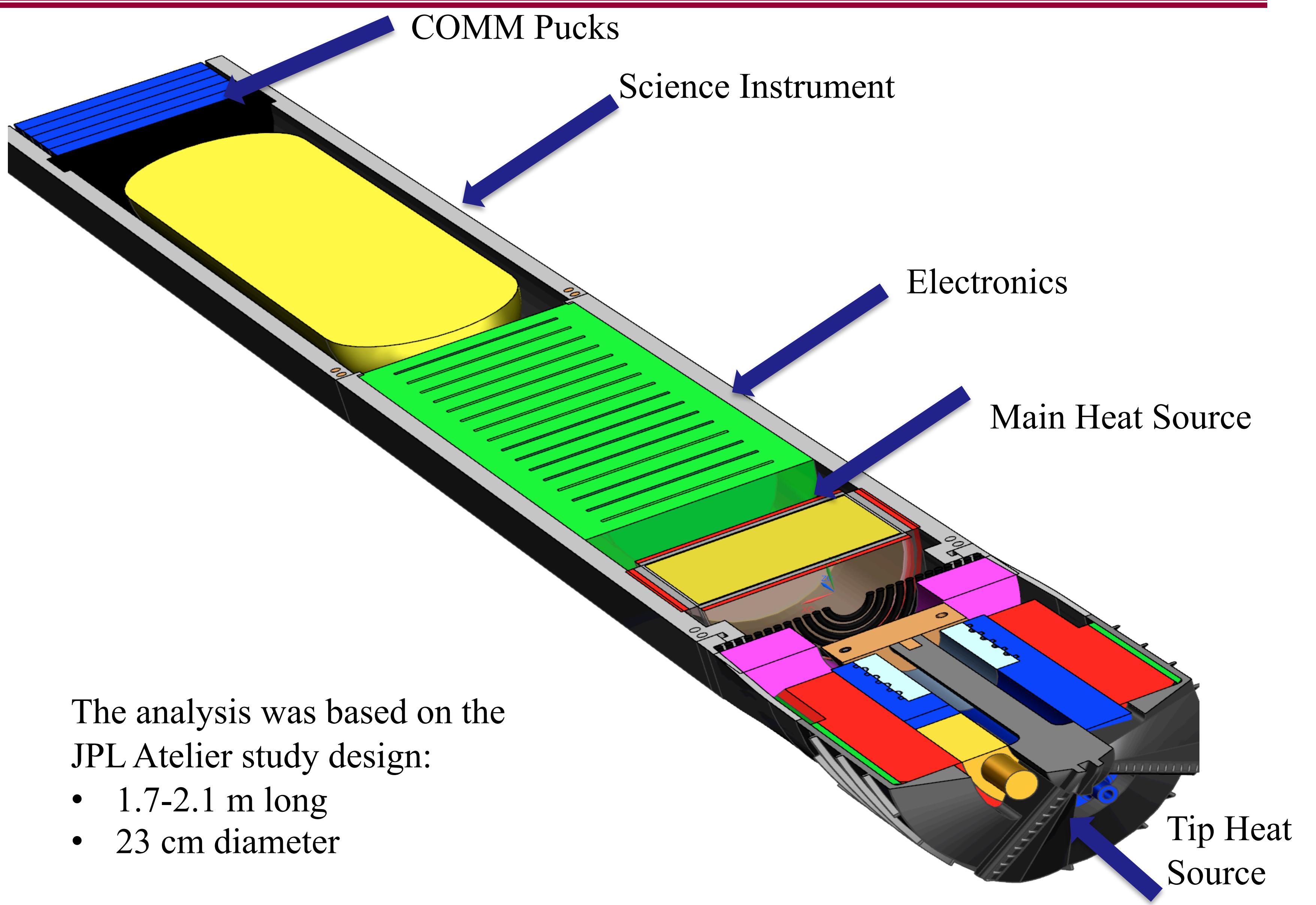
Analysis assumptions

- Variable Thermal Conductivity, C_p, density
  - Consistent with Atelier study
- Static Pressure- 560 psi. Assumed at a depth of 3 km.
- Model of stationary probe only

Ice and probe properties

- Ice Temperature: 160K
  - Ice temperature chosen at 3km depth of ice. At shorter depths, the main method used will be mechanical drilling due to porosity and sublimation
- Probe tip Heat source: 1kW
- Probe walls Heat source: 7.5kW
  - 7kW base from Atelier case
  - Assume constant heat across walls from internal 2 phase pump system
- Comm pucks Heat source: 1.25 KW

Initial Preliminary Notional Probe Designs



The analysis was based on the JPL Atelier study design:

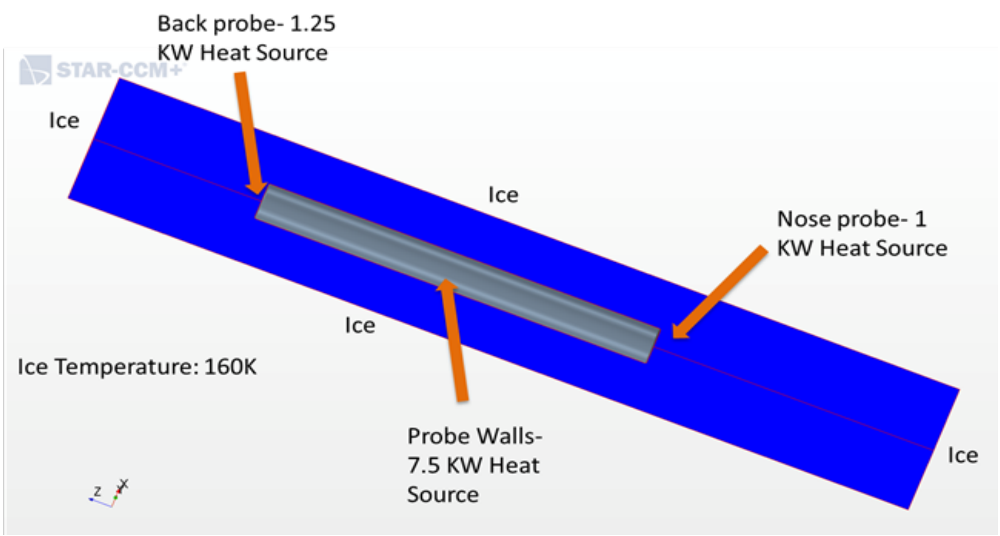
- 1.7-2.1 m long
- 23 cm diameter

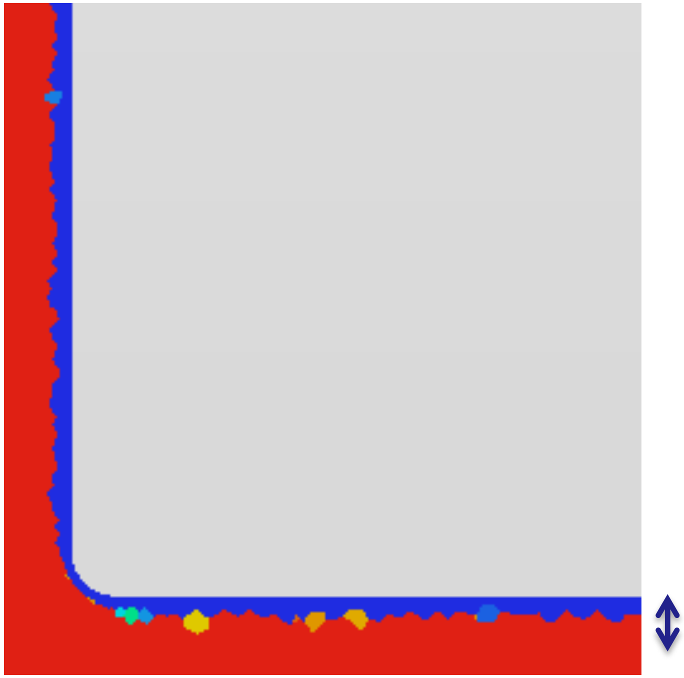
Descent velocity approximation for passive heating

Approach:

- Base rate of decent on velocity of receding liquid/solid ice interface.
- The liquid/solid interface will recede at different rates depending on distance from probe.
- Use rate of recession at the point in time when liquid layer rounds the bottom corner of the probe, and is fully formed along the sidewalls.
- At this point an actual probe would sink into the liquid water, pushing it out behind it.
- Probe walls Heat source: 7.5KW
- Heat Source at tip- 1 KW

- **Resulting Approximate Descent velocity: 9 cm/hr**



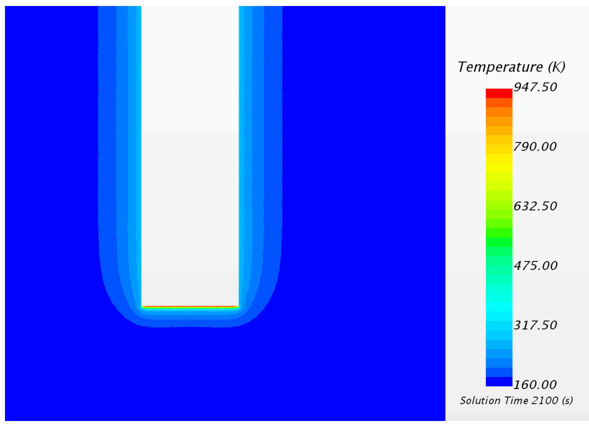


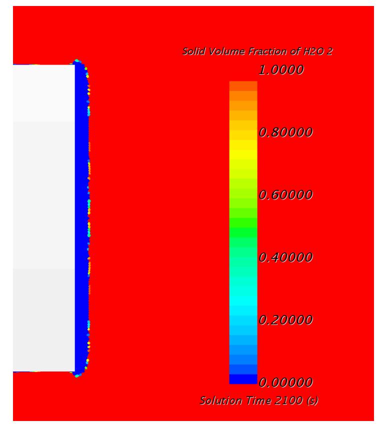
Courtesy: Nataly Brandt, Juergen Mueller

Directing more Heat to the tip

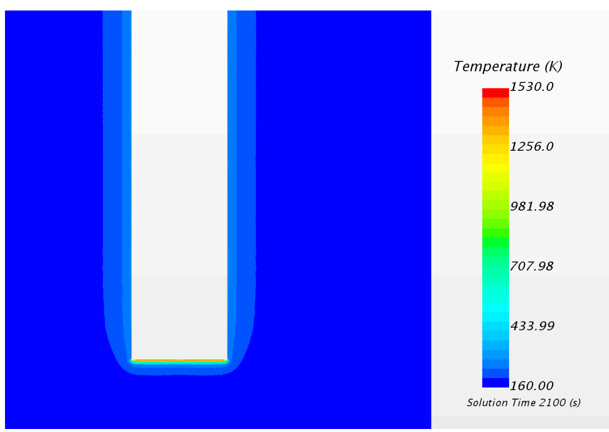
Heat at Tip	Melted ice in 5 min	Approx descent rate
1KW	7.6 mm	9.1 cm/hr
3KW	11 mm	13.2 cm/hr
5KW	15mm	18 cm/hr

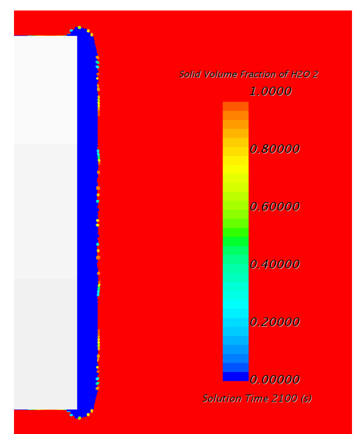
3KW at Probe tip





5KW at Probe tip





Courtesy: Nataly Brandt, Juergen Mueller

Melt rate is still not comparable to Water jets at 54cm/hr

Active Waterjet Configurations More Effective Location Comparison

Courtesy: Nataly Brandt, Juergen Mueller

- Water jet flow rate = 0.8 liter/min
- Water jets locations at 0.75 in, 1.25 in and 1.5 in from center

Location	Melt rate calculated at highest Δz	Melt rate calculated at lowest Δz
1.25 in	144 cm/hr	**54 cm/hr**
0.75 in	156 cm/ hr	**44 cm/hr**
1.75 in	Created difficulties around the corners. In reality, the water cannot go around the probe corners at these velocities, creating a Pressure build up at the tip pushing the probe back.	

- Active feeding achieves about 6-9 times the descent rate of the passive heating
- Could be higher once optimized

Water jet flow rate	Melt rate calculated at lowest Δz
0.8 liter/min	**54 cm/hr**
1 liter/min	**78 cm/hr**
passive	**9cm/hr**

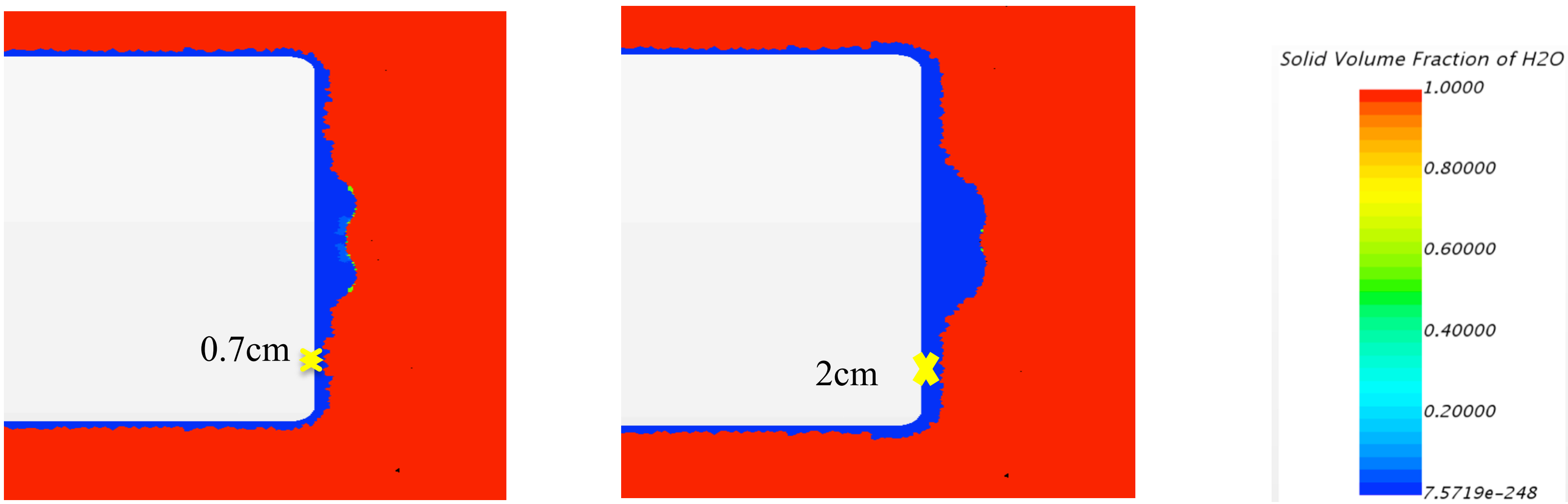
When the water jets are closer, the highest Δz > farther water jets. However, the probe would still be slower because of the melt rate at the edge of the probe

Active WaterJet Melting

Ice- 240 K

200 K	240 K

Liquid layer at 15 s



Ice Temperature	Δz (min)	Δz (max)	Melting rate (min)
200 K	0.7 cm	2.3 cm	168 cm/ hr
240 K	2 cm	7.5 cm	480 cm/hr

Courtesy: Nataly Brandt, Juergen Mueller

Melting rates at 200K and 240K are 168 cm/hr and 480 cm/hr

Summary

- Ice Penetration on Europa and Enceladus is Extremely Challenging
  - Temperature Conditions
  - Thermal Energy Requirements
  - Probe Size Limitations
  - At Least 3 Distinct Penetration Phases Identified:
    - Initial Start Phases – First Few 10's of Meters, Very cold, Very hard ice
    - Up to 3 km of depth – warmer, but still cold
    - Slow down phases as you reach ice / ocean interface
- Combination of Mechanical Drilling, Waterjet Melting and Passive Melting Required
- New RTG Designs Required to Deal with Large Temperature Differentials in this Application
- Requires New Heat Sources Designs with much Higher Thermal Dissipation Density
    - GPHS: Low Thermal Dissipation Density leads to large probe dimensions
    - New Microsphere-Based Heat Source Designs much more promising

ACKNOWLEDGMENTS

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