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New Thermoelectric Energy Harvesting Opportunities: Ocean Robotic Exploration Enabled by Ocean Hydrothermal Vents

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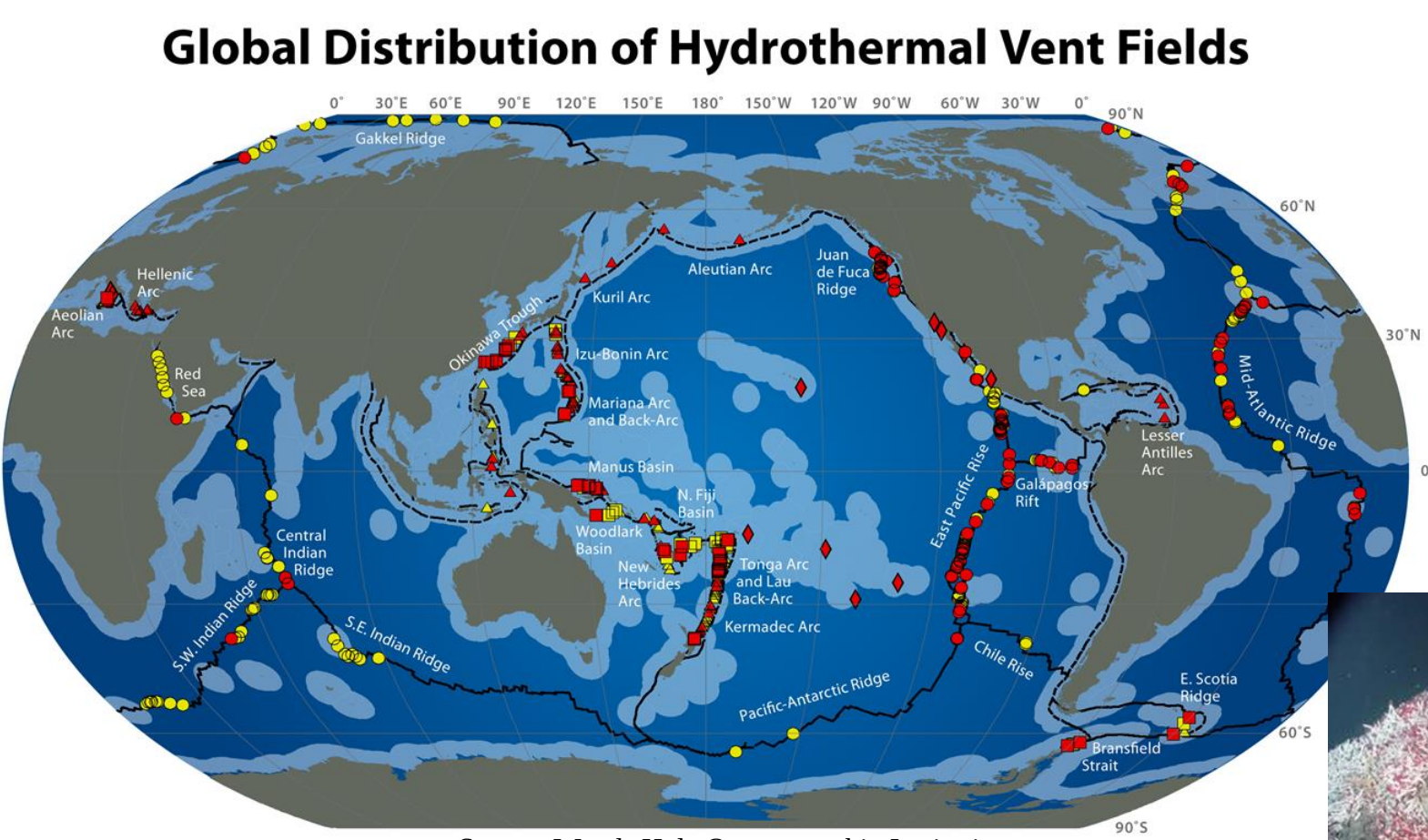
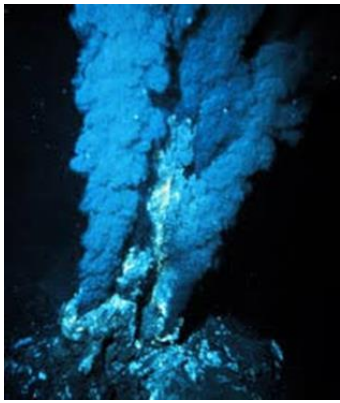
Location, Location, Location…..



Source: Woods Hole Oceanographic Institution



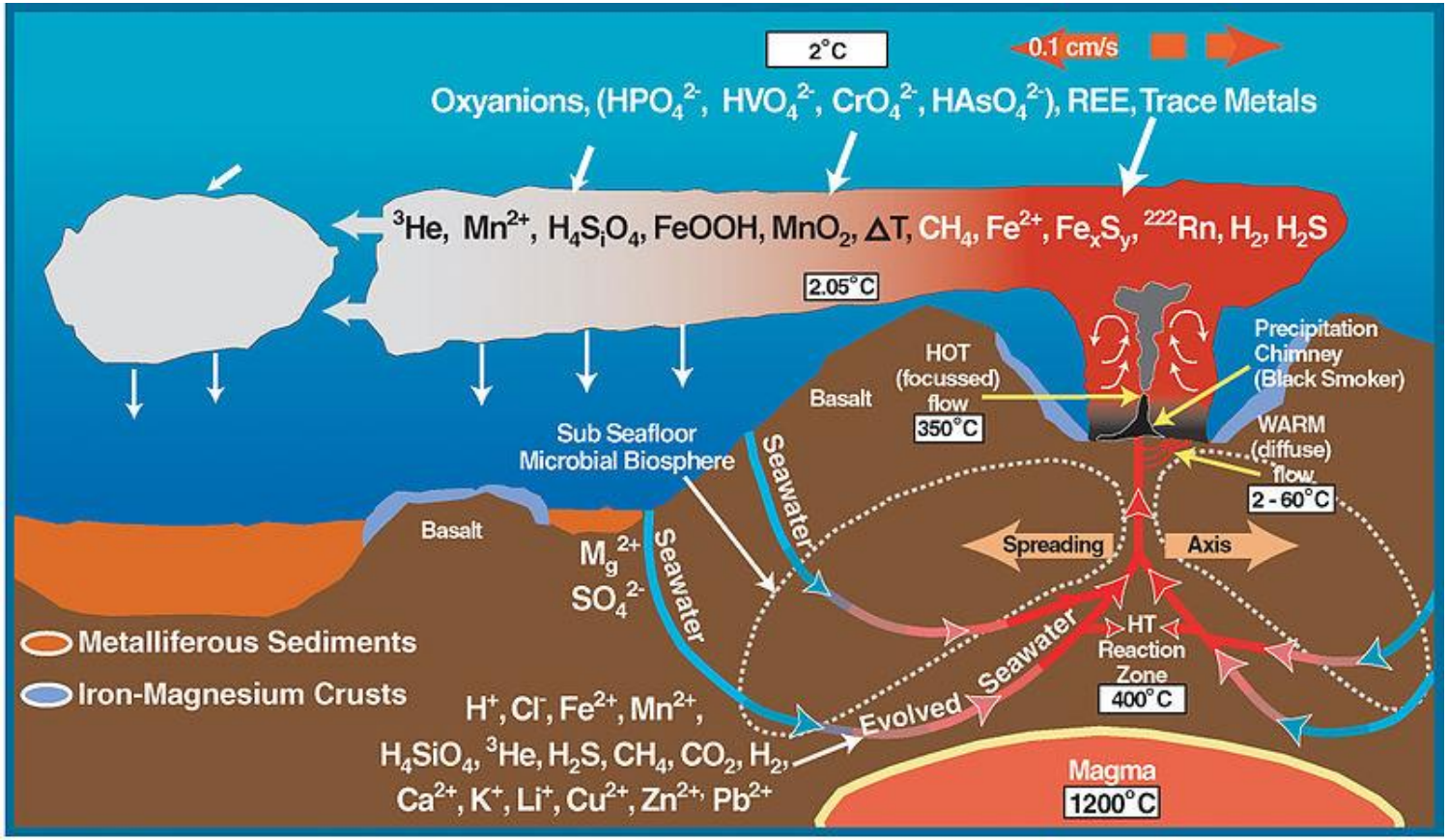
Source: MarineBio.net
Black Smokers (NOAA)

Source: National Ocean Service
National Oceanic and Atmospheric Administration

- Generally 3.6-5 km in depth
- Located generally around tectonic boundaries - Worldwide

Water Chemistry Near Hydrothermal Vent

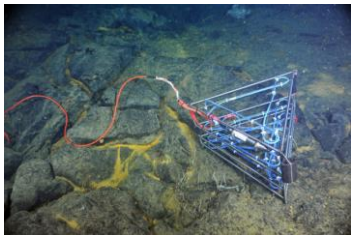
- Active and Complex Chemistry around Hydrothermal vent outlet
- Outlet Temperature can be 350-400°C
- Flow Velocity ~2 m/sec (3 different references quote this value)
- Available Thermal Energy >1 MW - We can capture and convert only a small fraction of this



Source: Wikimedia Commons

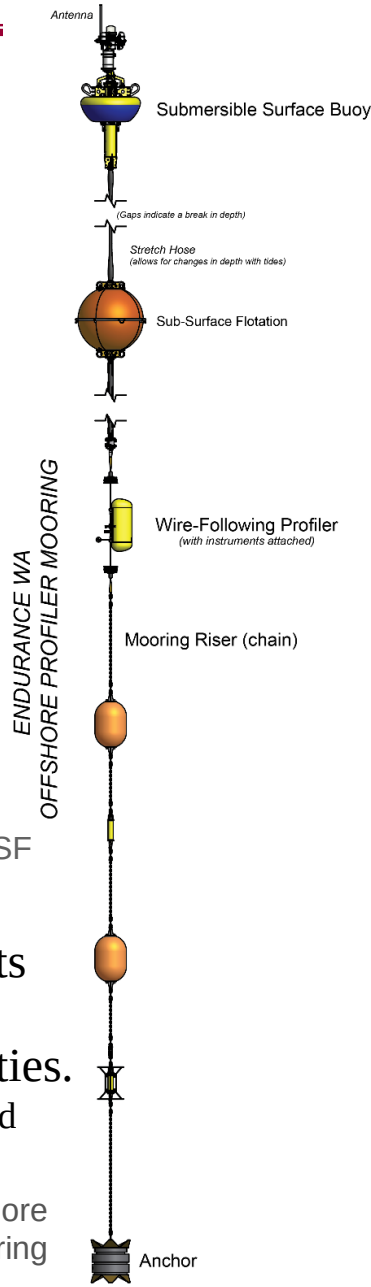
Useful Earth Science at Seafloor / Vents

- Water column measurements with depth (profilers, mooring cables)
  - Chlorophyll
  - Temperature
  - Dissolved O2
  - pH
  - Light transmission
  - Velocity of currents
- Monitoring at the vent or seafloor near vent (connected to cable, seafloor junction boxes)
  - Fluid flow at the sediment / water interface (outflow of gases like CH_4, H_2S)
  - Mass Spectrometer (methane, organics, gases, etc)
  - Imaging / Velocity meters (for long distances, but stationary)
  - **Digital stills and movies**
  - **Seismometers**
  - **Hydrophones**
  - **Dissolved O_2 meters**
  - Spectrophotometers



Thermistor Array: Custom from University of Washington. Photo credit: NSF-OOI/UW/CSSF

- Monitoring near vents is as important as monitoring the actual chimney – methane clathrates; seismic / volcanic activity; diffuse flows from sediments
- There are many, many types and varieties of each instrument for ocean science. They come from industry, military, and custom jobs from universities.
  - Example case: The OOI manages and integrates data from the over 800 instruments deployed amongst its seven arrays. https://oceanobservatories.org/instrument-class/vel3d/

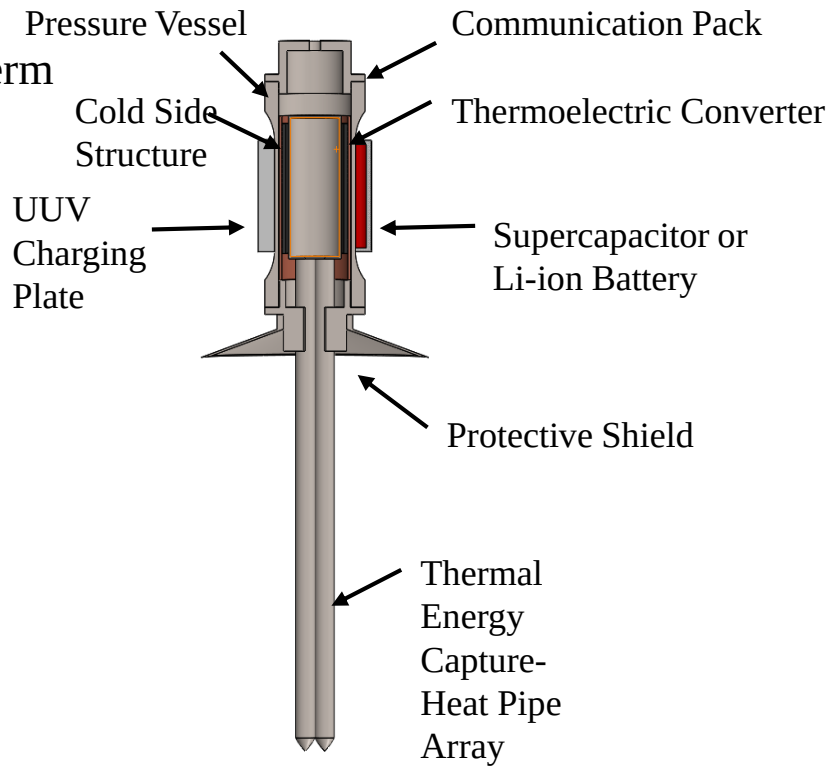


Endurance Washington Offshore Profiler Mooring

https://oceanobservatories.org/site/ce09ospm/

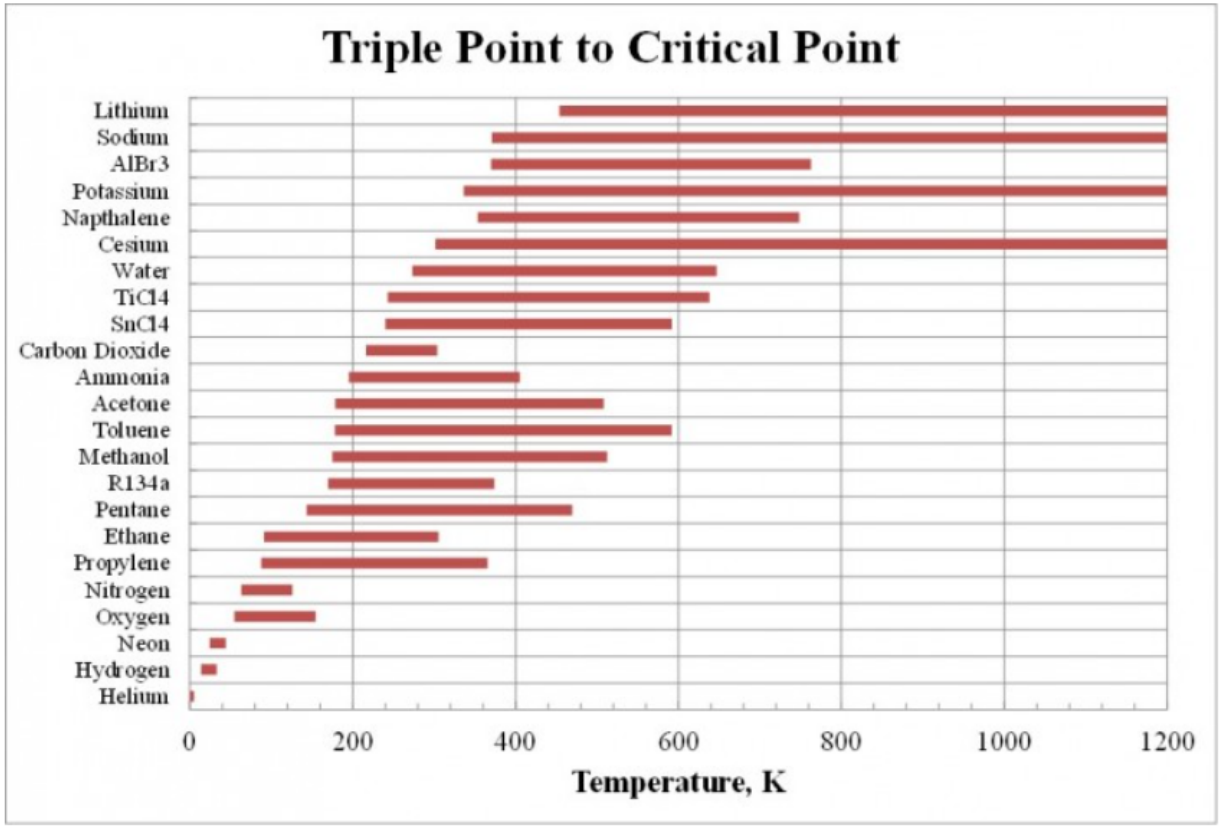
Hydrothermal Vent Power System Challenges & Description

- Hot-Side Thermal Absorption & Transfer to Thermoelectric (TE) Devices
- Cold-Side Dissipation from TE Devices
- Thermoelectric Device Design & Tailoring
- Supercapacitor or Li-ion Battery Design & Tailoring (+ Any power electronics)
  - Energy Storage is Key Capability for Long-Term Operations
- System Containment
  - Pressure (4265-7107 psi) (29.41-48.95 MPa)
  - Leakage
- System Integration
- Potential Mission Science
  - Earth's Oceans
  - Europa & Enceladus Oceans
- Communications
- CONOPS (Concept of Operations)



Heat Pipe Thermal Absorption Options

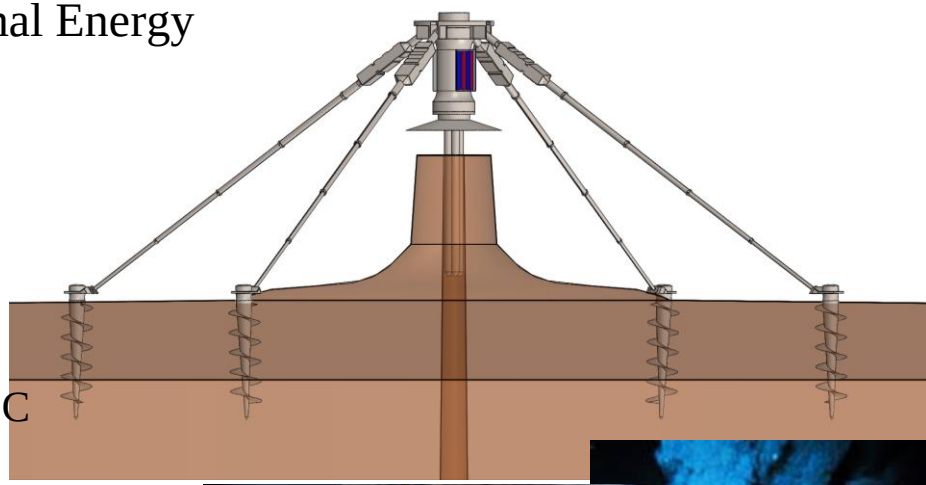
- 1000 W_{th} Thermal Absorption Goal
- Operating Temperature (T) Goal: 350°C – 400°C
- Potential Better Heat Pipe Operating Fluids at These Tempeatures
  - Sodium
  - $AlBr_3$
  - Potassium
  - Naphthalene
  - Cesium
  - Water
    - Low performance at this T



- 50 cm long evaporator section provides more thermal absorption
- Liquid Metals all Present Safety & Mission Success Issues, But Likely Workable

Hydrothermal Vent Power System Challenges & Description

- High Temperature Heat Pipes to Absorb Thermal Energy
- System Anchoring Envisioned
  - Heat Pipes Inserted into Vent Opening
  - Anchoring System to "Set It and Forget It"
- All-Skutterudite TE Technology
  - High Power Density
  - Performs Well at Temperatures up to 525°C-550°C
  - Much better than Bismuth Telluride
  - Could Eventually Segment Bismuth Telluride In
  - Measured TE conversion efficiency of ~9% at T_h = 425°C-35°C
  - Power flux of 2.1 W/cm^2 at these temperatures
  - Likely TE hot-side temperatures ~360°C
  - Likely TE cold-side temperatures ~20°C
- Planning to produce ~70-75 W_e depending on system thermal efficiency and final TE conversion efficiency



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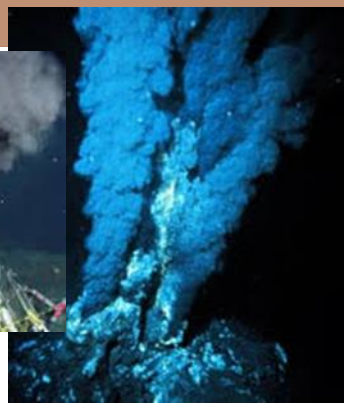

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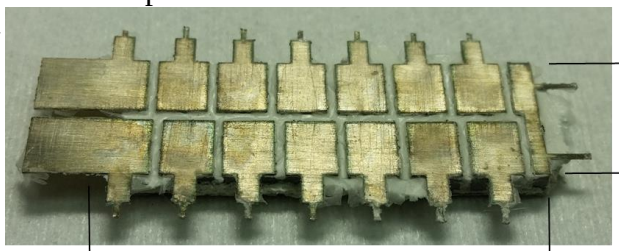


Thermoelectric Power Tradeoffs & Design Selection

Case Study 1:

TE Materials: P-Leg = p-type filled SKD, N-Leg = n-type filled SKD
T_{HOT} = 633.15K, T_{COLD} = 293.15K, Qin = 800W, Vmax = 30V

Conversion Efficiency: 8.37%
Vmax at Pmax = 0.0535V
Maximum Power: ~67W at Vmax = 30V

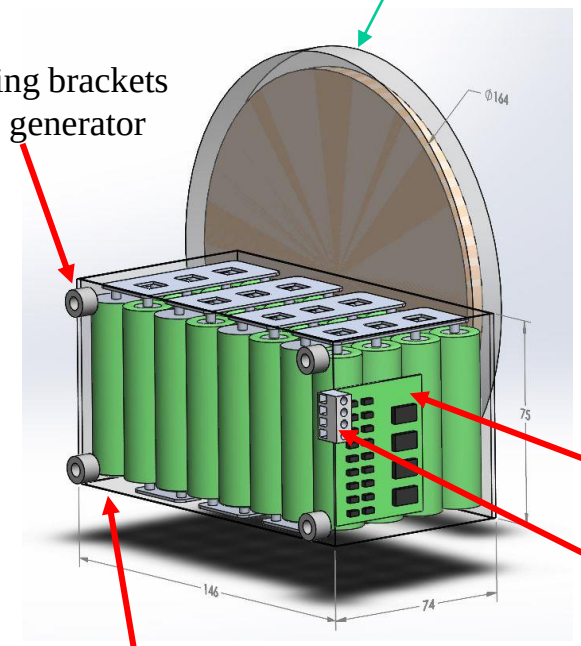
Height vs. Cross-Sectional Area Reduction Comparison

P_{LEG} & N_{LEG} TE Height (mm)	P_{leg} Length (mm)	P_{leg} Width (mm)	N_{leg} Length (mm)	N_{leg} Width (mm)	TE Material Total Area (P_{LEG} + N_{LEG}) (cm^2)
10.00	1.80	2.12	1.80	1.80	78.82
9.00	1.70	2.01	1.70	1.70	70.94
8.00	1.61	1.89	1.61	1.61	63.06
7.00	1.50	1.77	1.50	1.50	55.18
6.00	1.39	1.64	1.39	1.39	47.29
5.00	1.27	1.50	1.27	1.27	39.41
4.00	1.14	1.34	1.14	1.14	31.53
3.00	0.98	1.16	0.98	0.98	23.65

Hydrothermal Vent Battery Energy Storage

Inductive charging coil

Mounting brackets to TE generator



Battery BMS

Power connector TE generator

1 "unit cell" pack is shown here
Can add more in parallel to increase capacity/energy

Notional Pack Design

- **8s4p**
- **29V pack**
- **14 Ah capacity**
- **4 packs in parallel for 1.6 kWh total energy**
- **400 Wh energy/per unit cell pack**
- **Typical maximum charge rate is 2C to 4C per pack (3-6 hours)**
- **Maximum discharge current 40A per pack**
- **70ºC maximum operating temperature**
- **Typical lifetime: 400 cycles**

Remus 100

- **26.2V**
- **12.2 Ah**
- **1.37 kWh**
- **4 batteries in parallel**

Hydrothermal Vent System Science Power Loads

Instrument	Vendor	Voltage (V)	Power (W)	Comments
Communication Modem	Teledyne	27	20	
Mass Spectrometer	Harvard	24	72 to 192	24VDC@8A on startup; 24VDC@3A nominal
Camera	Rayfin	16.5 to 32.5	7.5 idle 8.5 recording 13.5 peak	
Camera	Sculpin	12-32	2.8	
Seismometer	Orcus		7.5 to 8	
Seismometer	Aquarius		0.190 to 0.200	
Doppler Profiler		13.5	20	
Oxygen & CO_2 Optode		5 to 14	0.5 to 1.4 (100 mA max)	
Spectrophotometer		10 to 35	8.3 to 28	
Hydrophone		24	2	
Temperature				
Acoustic Current Meter	ACM	5 to 12		

Vmax: 35V
Pmax: 192W
Imax: 8A

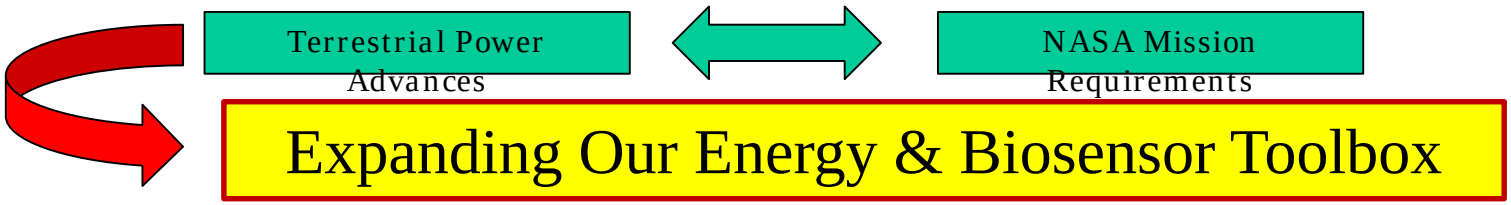
★ Key Primary Science & Capability

Communications

- **Incorporating a 960 Series ATM-966 Benthos Communications Device to enable intermittent deep-water communications to surface and UUV assets**
- **Key Features:**
  - 6000 meter depth rated modem
  - Low, MCompatible with new UTS-9400 Universal Topside Unit
  - Low, Mid, and Band C Frequencies available
  - No internal batteries, 12-36 VDC external power required
    - 24-36Vdc
    - 20W max in transmission –
    - 600 mW in receiving
    - 10 mW idle
    - 6 pins for cable connection power and data
  - Hard coat anodized aluminum housing.
  - http://www.teledynemarine.com/960-series-atm-966?Pr

Conclusions

- **High-pressure ocean hydrothermal vent power systems (OHyVeP) are part of our earth science and ocean worlds thrusts**
- **Thermoelectric power generation one of very few reliable, long-term power options**
- **OHyVeP can enable long-term UUV communications**, ocean seismometry, tsunami early warning, volcanism, ocean science (seafloor, sediments), oil detection
- Provides an opportunity for highly-reliable power for long-term ocean science an monitoring in deep ocean environments
- **Power station for UUV charging**
  - Continuous power output ~70 W_e
  - Incorporates integrated energy storage to enable rapid recharge of underwater assets
- **Reliable Communications** with surface and underwater assets



ACKNOWLEDGMENTS

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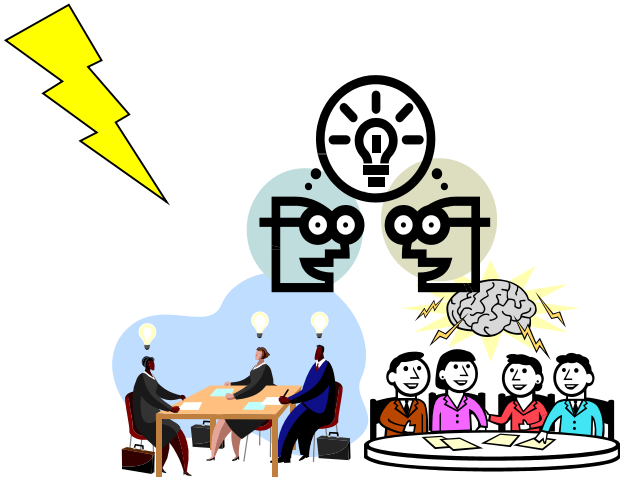
Thank you for your interest and attention

Some People See the World as It Is and Ask Why…… I Dream What Has Never Been and Ask Why Not? Robert F. Kennedy, 1968

Questions & Discussion