Power Systems for Spacecraft Missions Requiring Biosensor Technologies: Examples and Remaining Challenges

Dr. Ike S. Chi, Dr. Keith Chen, Dr. Erik Brandon, and Dr. Terry J. Hendricks

Jet Propulsion Laboratory, California Institute of Technology

4800 Oak Groove Drive, Pasadena CA 91109 USA

World Congress on Biosensors and Bioelectronics
Chicago, USA
August 20-21, 2018

Outline

- Overview of NASA/JPL's Past and Upcoming Spacecraft Missions Requiring Sensor Technologies
  - NASA's Habitable Worlds Program
    - Targeting on science relative to the Earth, moon, asteroids and comets, not just life
  - Examples of Our Sensing Technologies and Capabilities
  - Remaining Challenges
- Overview of a Reliable Power Systems for the Spacecraft Missions
  - Radioisotope Thermoelectric Generator (RTG)

NASA's Habitable Worlds Program

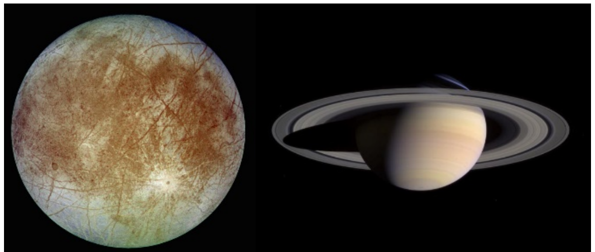
- To identify the potentially habitable environments in the Solar System and beyond
- To explore the possibility of extant life beyond the earth
- To develop the field of astrobiology through the NASA Astrobiology Institute (NAI)
- To provide scientific framework for future planetary exploration missions

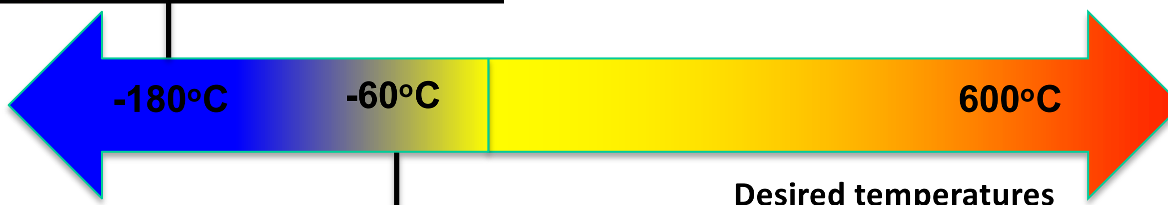
"……, no longer is the main question whether bodies like Mars or the outer Solar System's icy moons could be habitable. Rather, researchers have moved on to determining how they can find evidence of life, past or present, through the **presence of bio-signatures and other techniques.**" …… Astrobiology Science Conference (AbSciCon) 2017

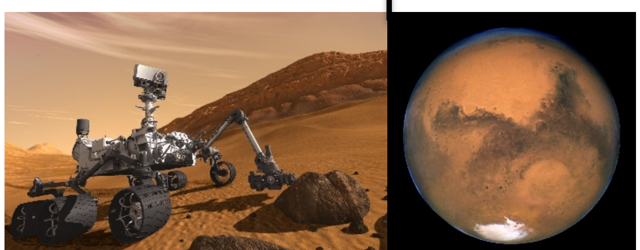
Targeting on science relative to the Earth, moon, asteroids and comets, not just life

Extreme Environments

Jupiter's moon Europa







Mars

Extreme environmental conditions for planetary missions (e.g., temperatures, gravity, thermal shock, radiation, and chemical attack)

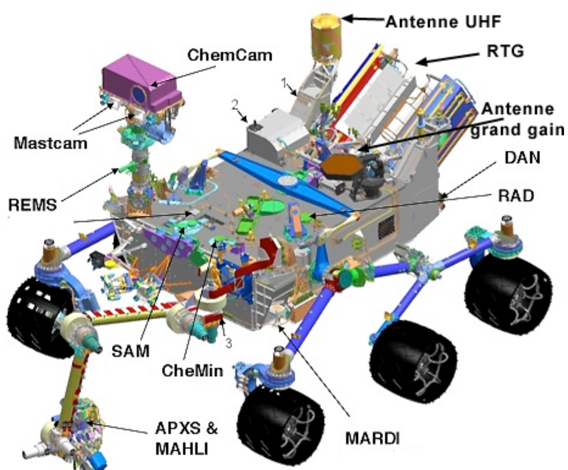
Habitable Worlds Program
Solar System Exploration Missions
(Follow the Water)

NASA's Mars Science Laboratory (Curiosity Rover)

- Landed the Curiosity Rover on Mars in 2012 - **Sky Crane**
- About the Size of a Small Car (~2000 lbs)
- Radioisotope-Driven Thermoelectric Generator (RTG) Used to Power Curiosity

- Curiosity set out to find out if Mars ever have the right environmental conditions to support small life forms (microbes)

- Curiosity's *in-situ* scientific tools found chemical and mineral evidence of past habitable environments (Rivers, Lakes, & "Oceans") on Mars



Cameras:

- Mast Camera (MastCam), Mars Hand Lens Imager (MAHLI), Mars Descent Imager (MARDI)

Spectrometers:

- Alpha Particle X-ray spectrometer (APXS), Chemistry and Camera complex (ChemCam), Chemisrty and Mineralogy (CheMin), Sample Analysis at Mars (SAM)

Radiation Detectors:

- Radiation assessment detector (RAD), Dynamic Albedo of Neutrons (DAN)

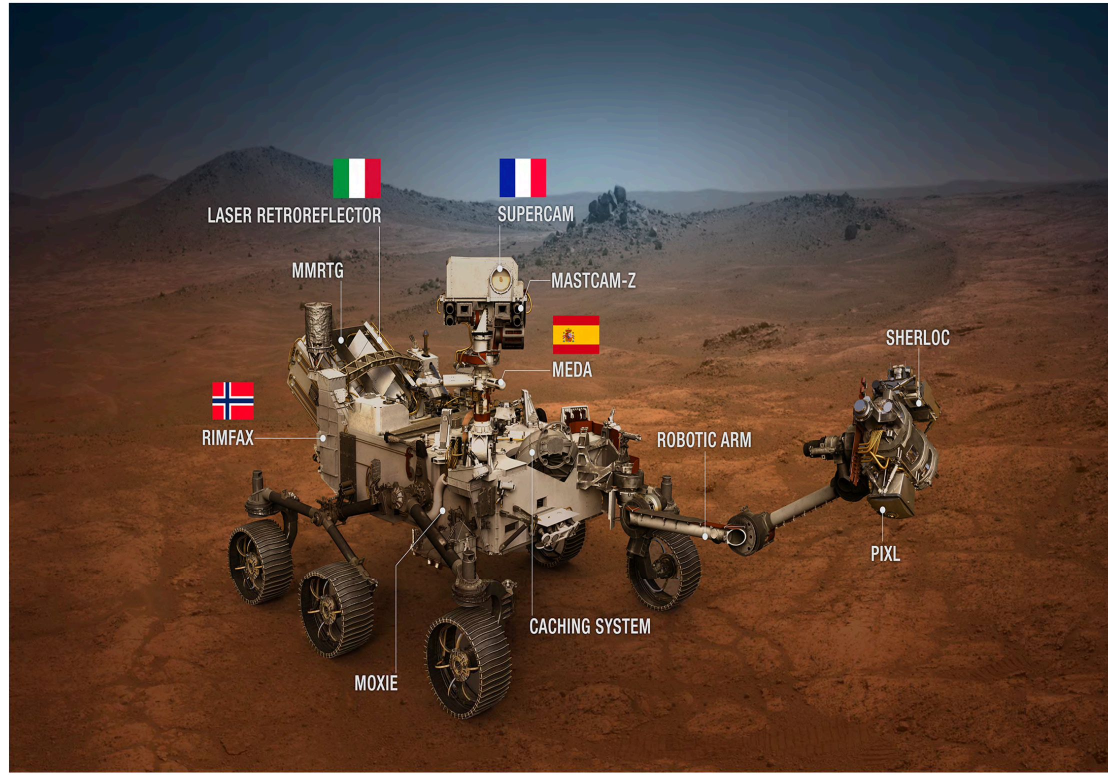
Environmental Sensors:

- Rover Environmental Monitoring Station (REMS)

Atmospheric Sensors:

- Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI)

Mars 2020 Scientific Instruments



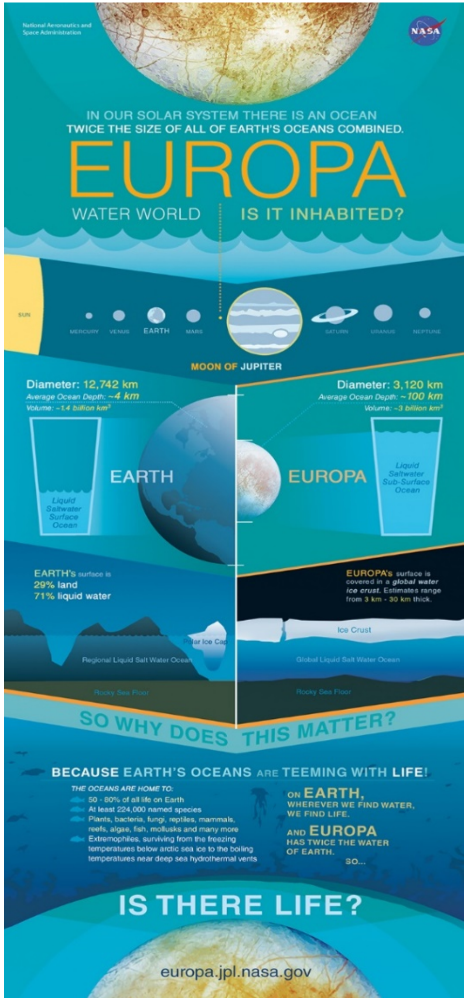
Mission Objectives

- Seek signs of habitable conditions and microbial life on Mars in the ancient past
- To gather knowledge and demonstrate technologies that address the challenges of future human expeditions to Mars
- Test a method for producing oxygen from the Martian atmosphere

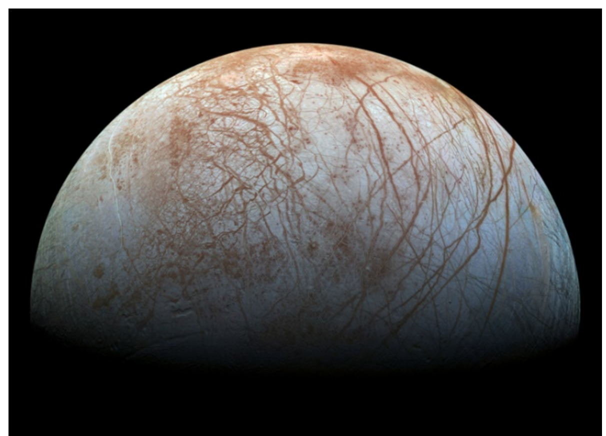
More advanced state-of-the-art scientific instruments

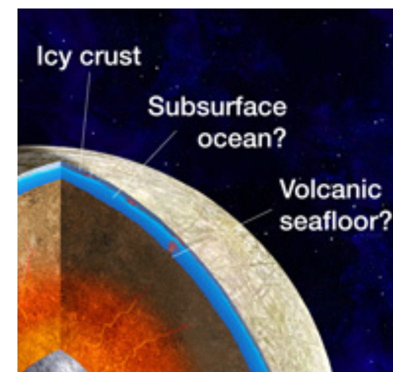
- Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) sensors
- An ultraviolet Raman and fluorescence spectrometer which will be mounted on the rover’s robotic arm and will search for organics and minerals that may be signs of past microbial life

Opportunities of Scientific Instruments for a Potential Jupiter's Europa Ocean Worlds Lander



- Europa is a moon that orbits the planet Jupiter
- Europa's surface is mostly solid **water** ice
- ***Europa might be the place to look for environments where life could exist in the present day***
- Life as we know depends upon three key "ingredients"
  - Liquid **water**
  - Essential chemical elements/reactions
  - A source of energy
- **Lots of opportunities for biosensor/bioelectronics communities for a potential lander/rover mission**





Cutaway diagram of Europa's interior

Advancements in Our Scientific Instruments

Table top system
(~100 lbs)

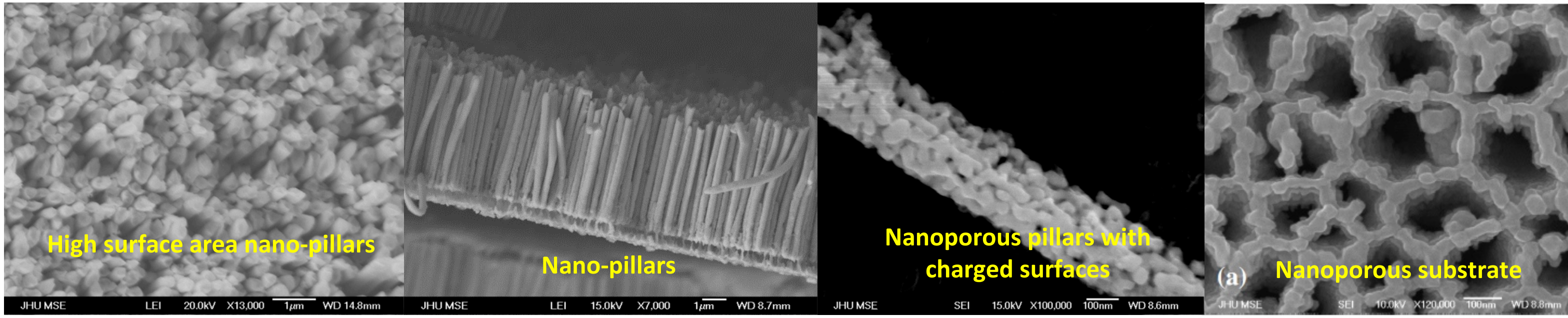
Commercially available system (< 5 lbs)

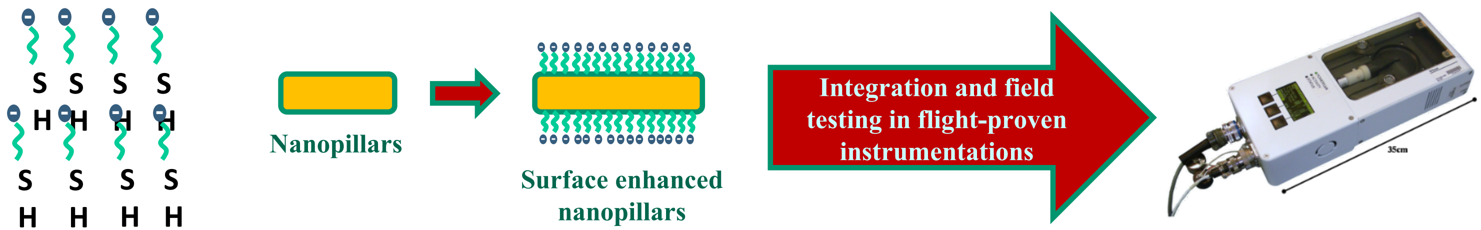
Our Key Objectives

- Multi-platform ***in-situ*** bio/chemical sensors on **ultra-trace (ppb)** analyte concentrations under **extreme environmental conditions**
- **Low power**
- Highly portable and scalable (**reduce the payload**)
- **Non-destructive technique**
- Fast response and short detectable reaction-time
- Targeted analytes
  - Gas sensor – hydrogen, oxygen, nitrogen, CO_2, etc.
  - Raman laser bio/chemical sensor – carbohydrates, amino acids, phosphorus, iron, magnesium, sodium, etc.

Hand unit (< 2lbs)

Our Technology Development Approach



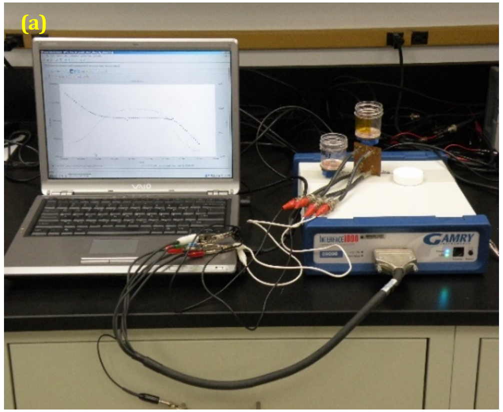


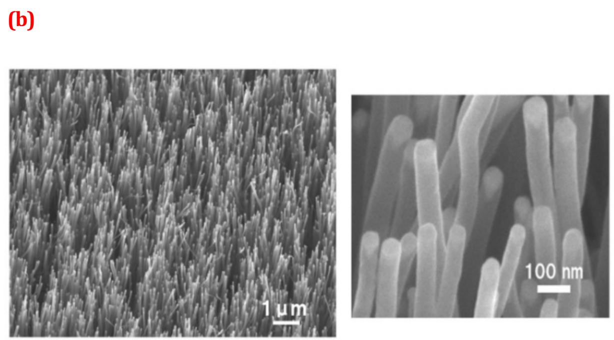
Novel engineered nanostructured electrodes can be retrofitted into spacecraft-proven sensing platforms

- Active surface area of the electrode to **~1000 m^2/g to enhance sensitivity and selectivity**
- Electrode materials:
  - Au, Ag, Pd, Pt, Ti-based alloys, CoCr alloys, and doped or un-doped biocompatible semiconducting materials
- Tailor the surface porosity and morphology using various techniques

I. Chi, S. L. Farias, and R. C. Cammarata, *ECS Trans.* 2012 **41**(35): 119-122.

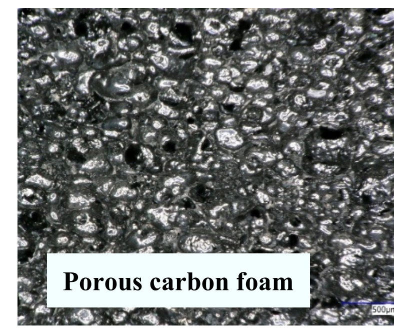
Carbon-Based Electrodes for Ultra-trace Sensitivity





Porous carbon foam block

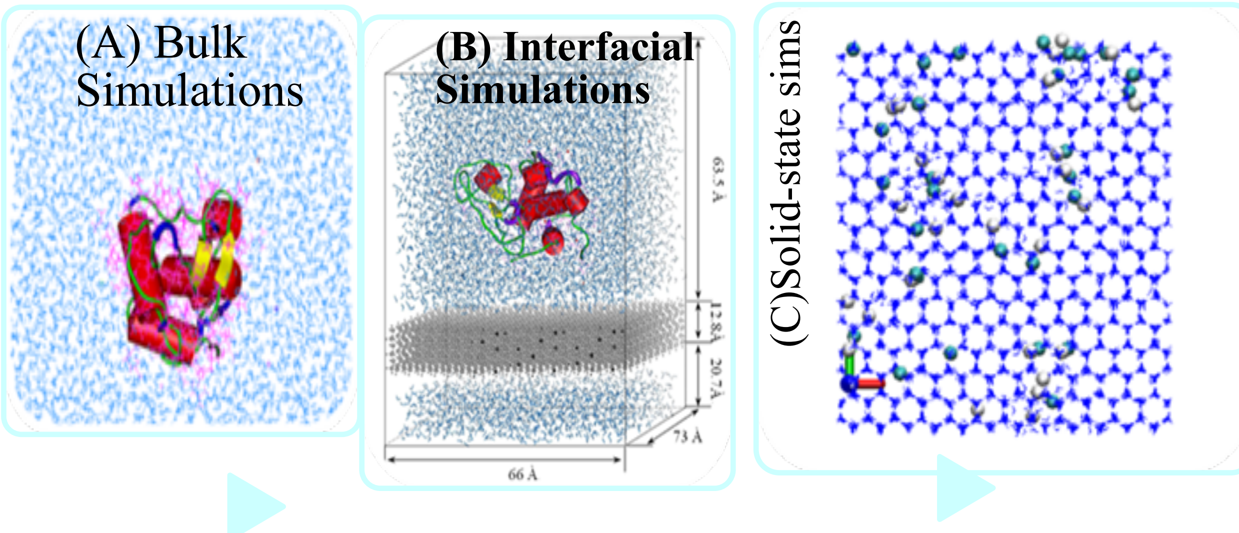
- **Single-walled carbon nanotubes (SWCNTs) and graphene materials to increase the active surface area of sensing electrodes**



Porous carbon foam

- **Applications to wide range of missions**
  - Human expedition missions
    - Habitable environments
    - Future planetary exploration
  - Space exploration missions
    - *In-situ* sensing in extreme environmental conditions for planetary missions
    - Landers/rovers on Venus, Mars, icy moons of Jupiter and Saturn

Molecular Modeling and Atomistic Simulations Supporting Sensor Technologies



JPL and academia collaborative efforts are underway to develop critical chemical/physical mechanisms in support of developing sensor technologies

- Bulk transport properties
- Interfacial electrode/electrolyte properties
- Charge-transfer properties

Amico Acids Characterization using Impendence Spectroscopy Technique with Polarizable Microelectrode

- The detection of amino acids in extraterrestrial environments is of particular interest to the astrobiology community

- Characterize amino acids in an aqueous environment by electrochemical impedance spectroscopy (EIS) using polarizable electrodes

- Sensitivity level: part per billion (ppb) concentration (~ 1 mM)

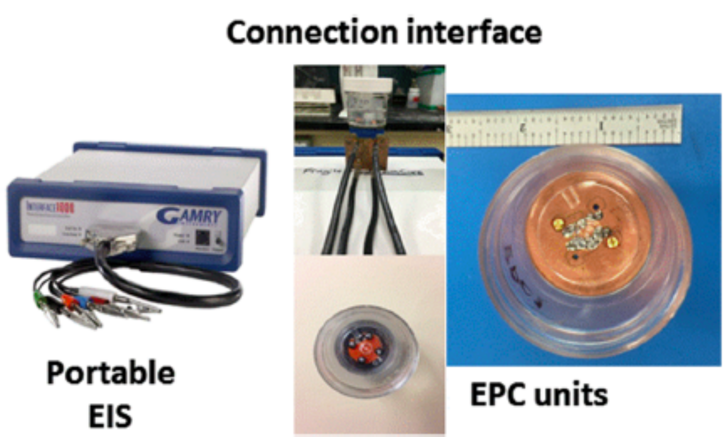


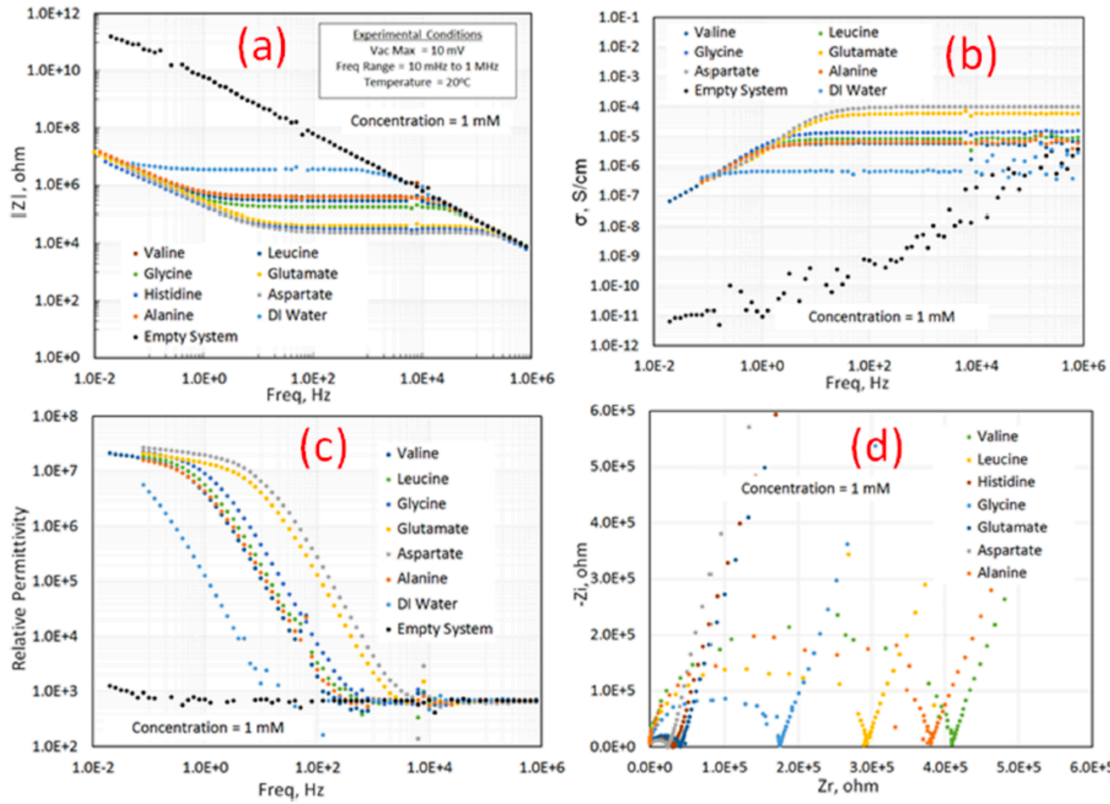
TABLE I. Summary of known physical and chemical properties of amino acids.

Amino acid	MW	Hydropathy	Chg	Solubility[a]
Ala	71.1	Hydrophobic	N	15.8
Asp	115	Hydrophilic	–	0.42
Glu	129	Hydrophilic	–	0.72
Gly	57.0	Hydrophobic	N	22.5
Leu	137	Hydrophobic	N	2.37
Val	113	Hydrophobic	N	5.6
His	99.1	Moderate	+	4.19

[a]Solubility in gm per 100 gm water.

K. B. Chin, **I. Chi**, J. Pasalic, C-K Huang, and L.M. Barge, *Review of Scientific Instrument* **89**, 045108 (2018).

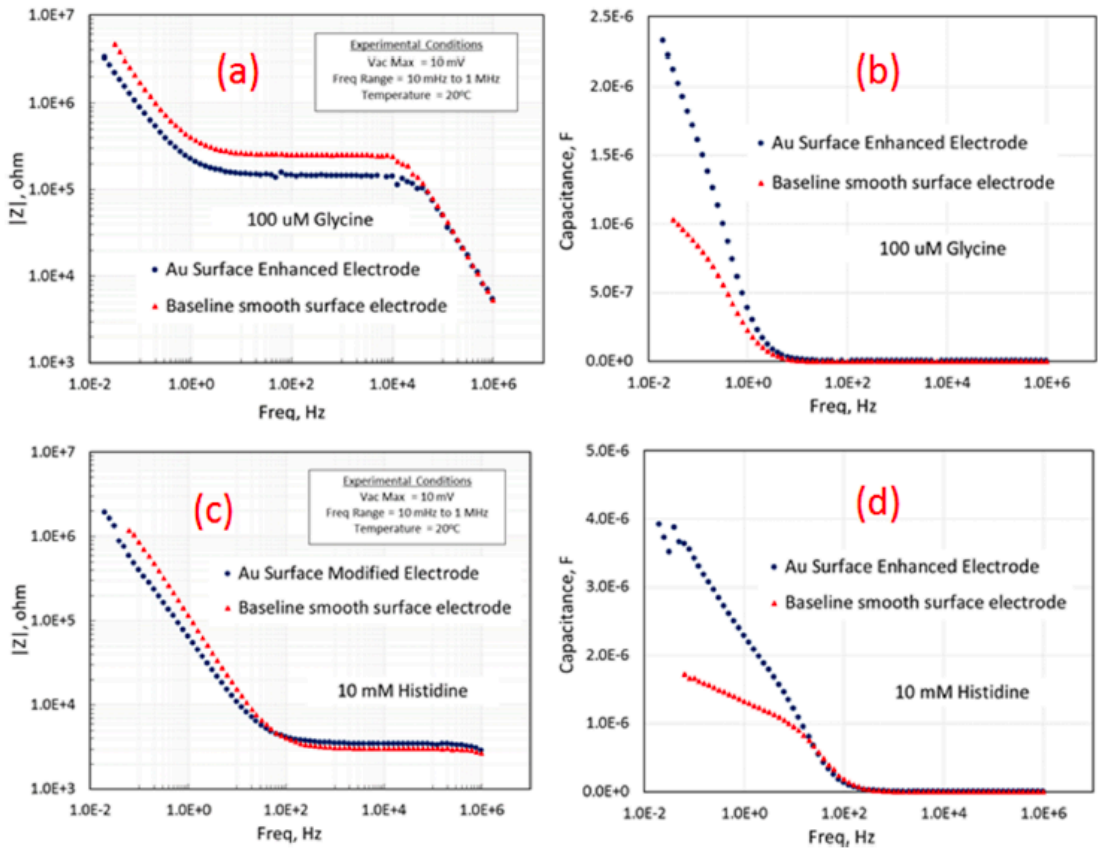
Sensing Capability of Amino Acids



- Polar amino acids (*i.e.*, Asp and Glu) exhibited higher electrochemical activity
- Non-polar amino acids (*i.e.*, Ala, Gly, Val, and Leu) showed lower electrochemical activity

K. B. Chin, **I. Chi**, J. Pasalic, C-K Huang, and L.M. Barge, *Review of Scientific Instrument* **89**, 045108 (2018).

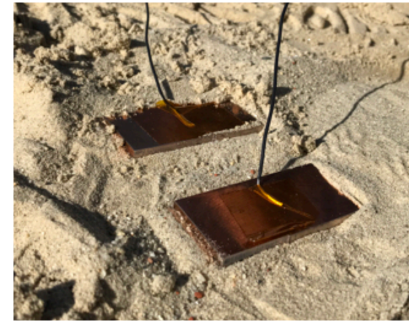
Detection Sensitivity Enhancement with Electrode Surface Modifications



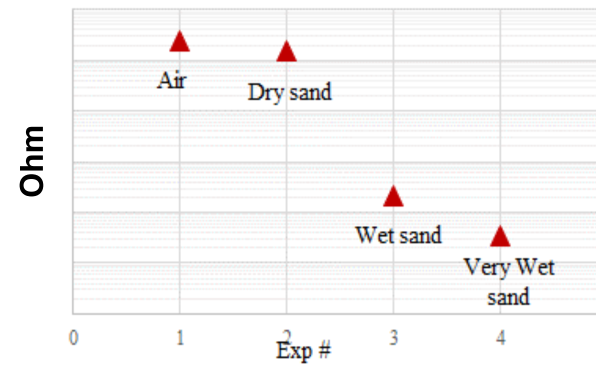
Increasing the electrode active surface area showed the improvement of sensitivity of the device

K. B. Chin, **I. Chi**, J. Pasalic, C-K Huang, and L.M. Barge, *Review of Scientific Instrument* **89**, 045108 (2018).

Electrochemical Sensor Applications – “Smart” Tactile Wheel



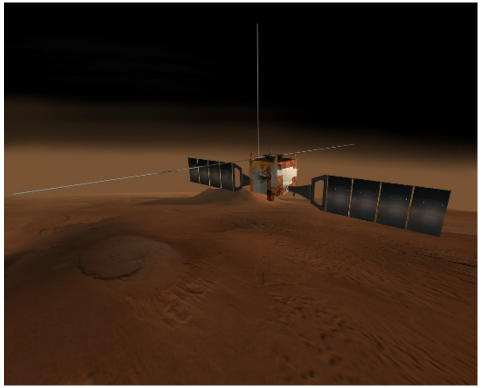
JPL’s Mars Yard Demo Test



Attempt for Mars 2020 by JPL to integrate electrochemical sensors as moisture detectors for *in-situ* planetary surveying

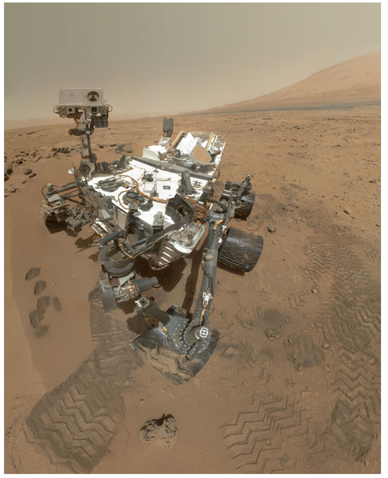
Remaining Challenges

- **Remote Detection – Spacecraft/fly-by missions**
  - Advantages:
    - Orbiters tend to be less expensive than landers
    - Greater surface area of the planet or moon can be investigated with a given technique
  - Challenges:
    - The limits of detection for biomarkers are poor and resolution may be insufficient to allow for unequivocal detection of life



***Mars Express* orbiter**

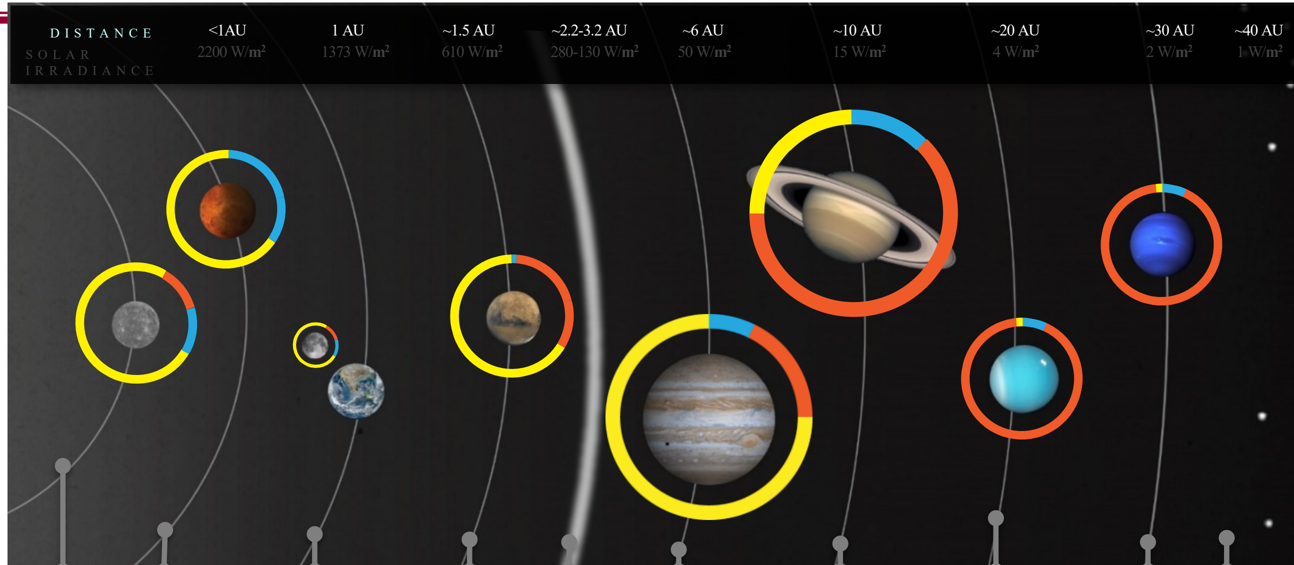
- **Direct Detection – Landers/Rovers**
  - Advantages:
    - *In-situ* techniques have many benefits, such as sensitive limits of detection for biomarkers like amino acids
    - Landers/rovers can potentially move rocks or drill holes, accessing areas less likely to be sterilized by ultraviolet radiation or other surface weathering effects
  - Challenges:
    - *In-situ* detection strategies are more susceptible to contamination, and must carry appropriate controls to mitigate false positives



Curiosity Rover

Reliable Power Systems for Science Exploration Space Missions

POWER TECHNOLOGIES APPLICABLE TO SOLAR SYSTEM EXPLORATION MISSION CONCEPTS AS OF 2015(1)



MERCURY
SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

VENUS
SOLAR
- Orbiters
- Upper Atmosphere Probes*
- Surface Probes**

RPS
- Current RPS not operable in Venus surface environment

BATTERIES
- Atmospheric probes
- Surface Missions

MOON
SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

MARS
SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Long-lived Polar Lander
- Long-lived, high capability rovers

BATTERIES
- Short-lived surface missions

ASTEROIDS
SOLAR
- Sample Return
- Flybys/Tours
- Orbiters
- Landers

RPS
- May be necessary for Trojan asteroids

BATTERIES
- Short-lived surface missions

JUPITER
SOLAR
- Orbiters
- Flybys

RPS
- High capability
- orbiters
- Long-lived moon landers

BATTERIES
- Atmospheric Probes
- Short-lived landers

SATURN
SOLAR
- Flyby s/c
- Orbiters

RPS
- High-capability orbiter
- Ring observer
- Titan Montgolfier (MMRTG)
- Long-lived surface mission

BATTERIES
- Atmospheric probes
- Short-lived surface missions

URANUS
SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys

BATTERIES
- Atmospheric probes

NEPTUNE
SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Long-lived Triton Lander

BATTERIES
- Atmospheric probes

KUIPER BELT
SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Landers

BATTERIES
- Short-Lived landers

*requires technology development for solar cells in corrosive environment
**requires technology development for high temperature

Legend: Solar (yellow); RPS (Nuclear) (orange); Primary Battery (blue)

(1) Notional mission applicability based on expert opinion developed in JPL A-Team study in August, 2015

Pre-Decisional Information — For Planning and Discussion Purposes Only

Prefer low power consuming scientific instruments/sensors

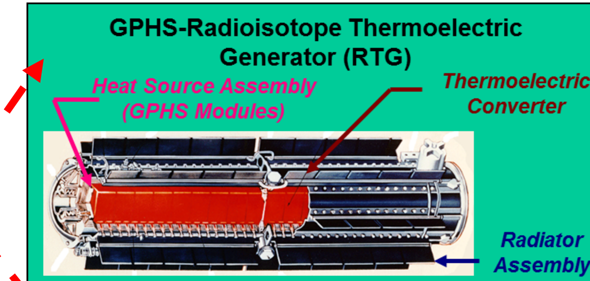
NASA Science Exploration Missions Need for Both Solar & Radioisotope Power Systems (RPS)

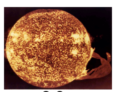
Solar power systems serve a *critical role* in the scientific exploration of the near-Earth solar system

- Moderate power levels up to 100 kW
- Operations **dependent** on distance and orientation with respect to Sun

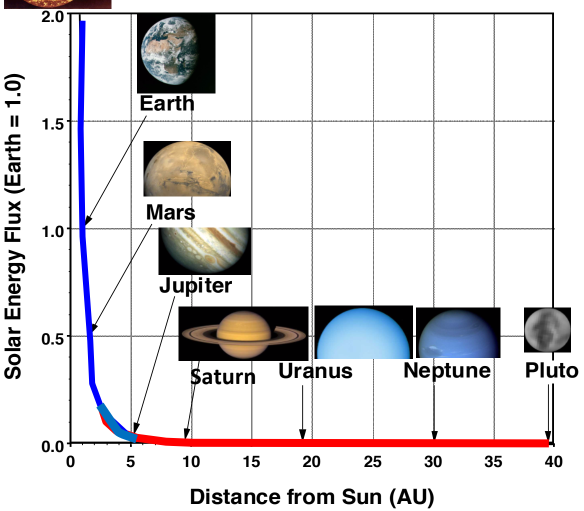
Radioisotope power systems (RPS) serve a *critical role* in the scientific exploration of the deep-space solar system

- Low to moderate power levels (~100 W - 1 kW) for more than several months
- Operations **independent** of distance and orientation with respect to Sun

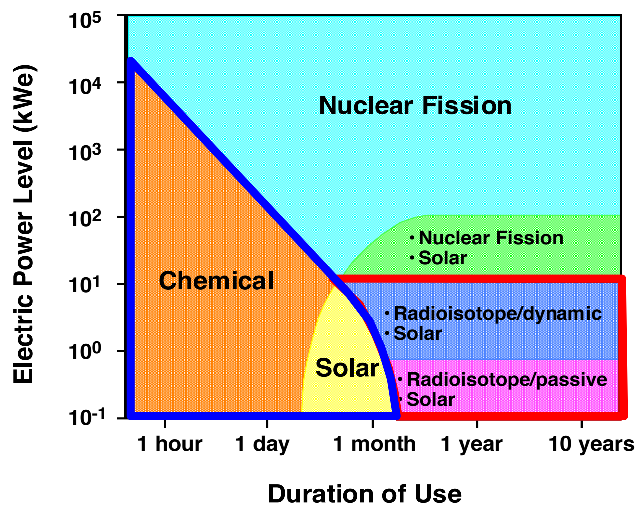


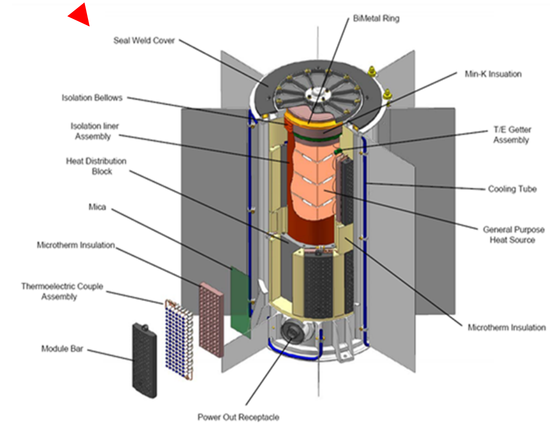


Inherent limitation of solar power



Best candidates for maximizing specific power (W/Kg)



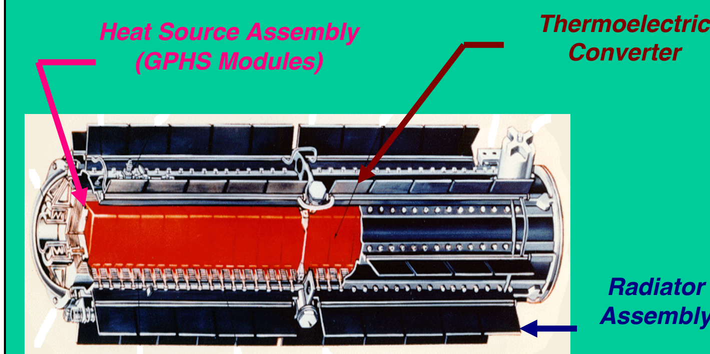


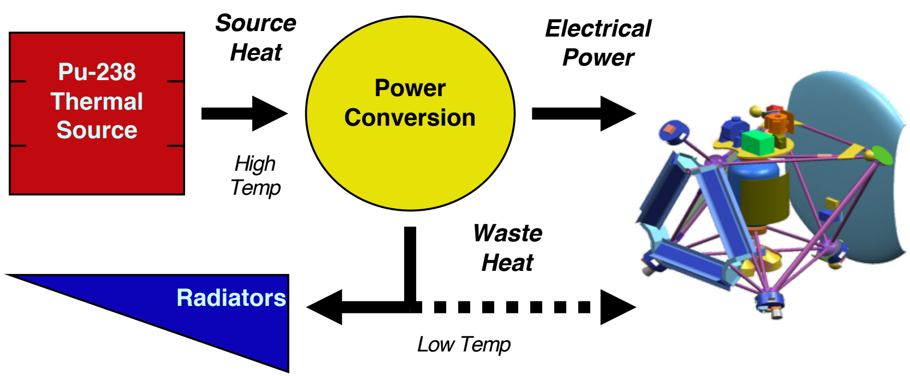
Multi-Mission RTG (MMRTG) Curiosity Rover on Mars

Overview of a Radioisotope Power System

- **High grade heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)**
  - 87.7-year half-life
  - Heat source temperature ~ 1300 K
- **Portion of heat energy converted to electricity via passive thermal cycles (6%-35%)**
  - Thermoelectric (existing & under development) and Stirling
- **Waste heat rejected through radiators or a portion can be used for thermal control of spacecraft subsystems**

GPHS-Radioisotope Thermoelectric Generator (RTG)



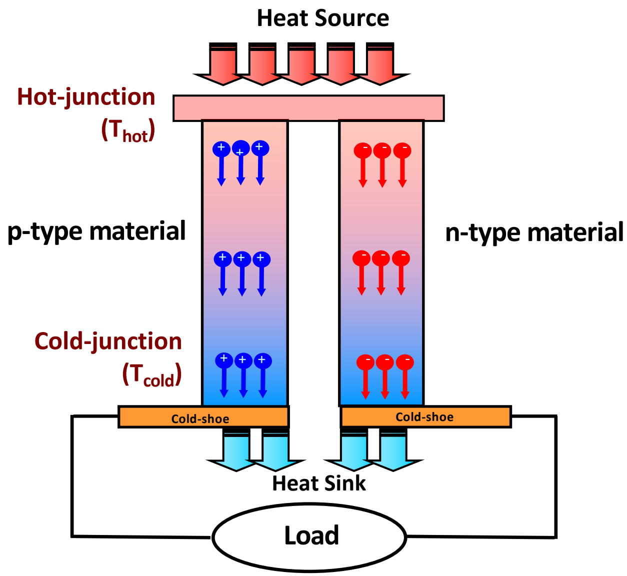


RTG performance characteristics

- Specific power (W/kg) → Direct impact on science payload
- Thermoelectric converter efficiency → Reduces PuO_2 needs
- Power output → Supports diverse mission profiles

Thermoelectric (TE) Power Generation

Thermoelectric p-n junction/couple

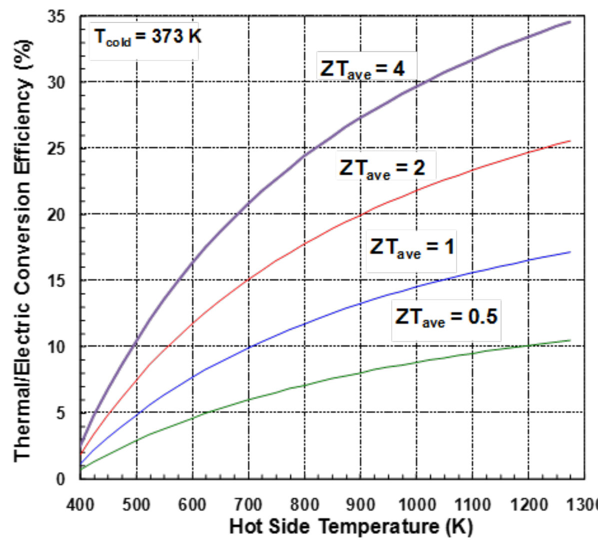


Seebeck effects are defined by the electrical currents induced by a temperature gradient

Dimensionless Thermoelectric Figure of Merit, *ZT*

$$ZT = \frac{\sigma S^2 T}{\lambda} = \frac{S^2 T}{\rho \lambda}$$

Seebeck coefficient, S
Electrical conductivity, σ
Electrical resistivity, ρ
Thermal conductivity, λ
Absolute temperature, T



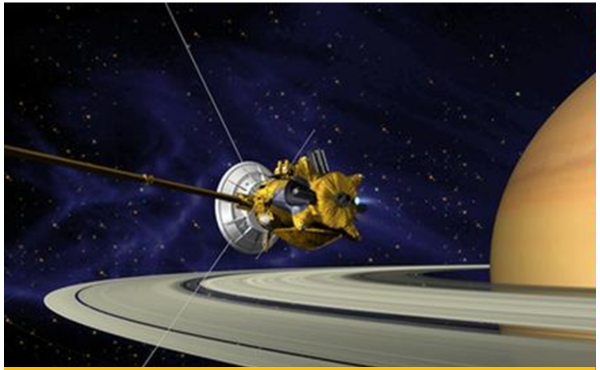
Current State-of-the-art TE Materials

Bi_2Te_3 300 K – 525 K
PbTe-based 400 K – 775 K
SiGe-based 525 K – 1273 K
Skutterudites 475 K – 875 K
$La_{3-x}Te_4$/Zintls 625 K – 1273 K

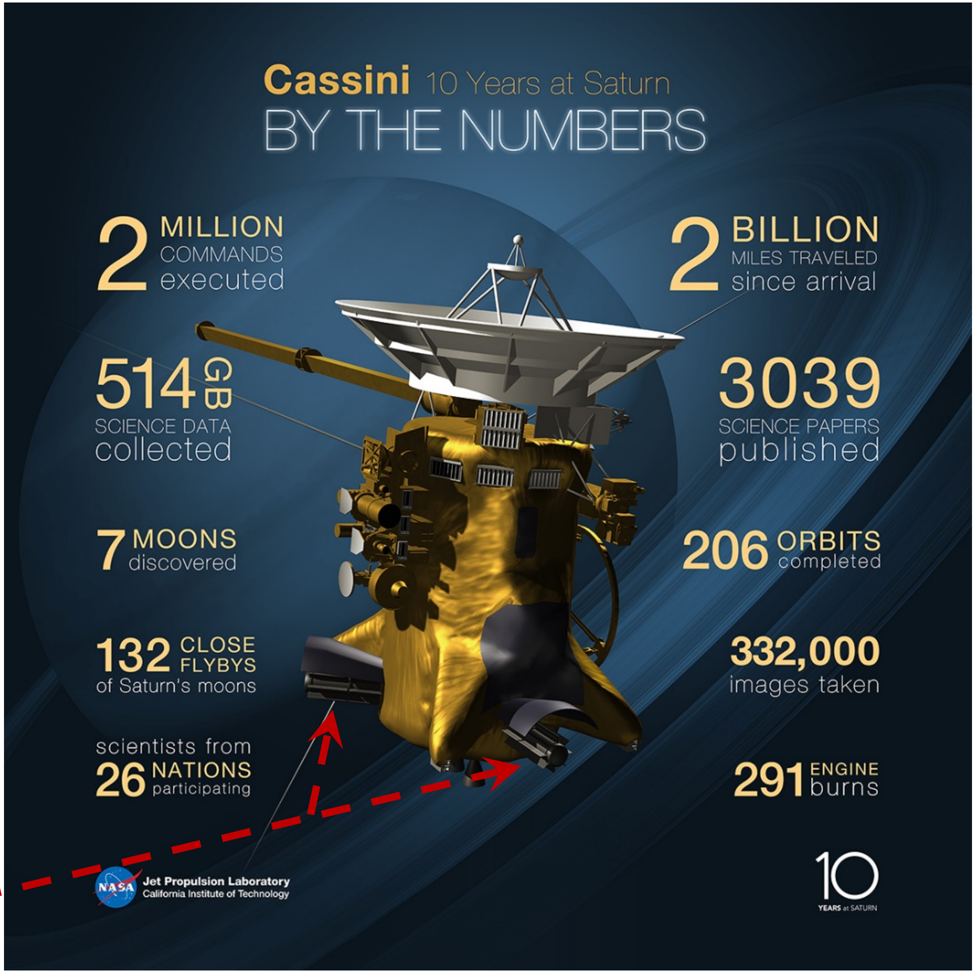
TE device conversion efficiency is a direct function of ZT (TE material properties) and ΔT

CASSINI Spacecraft to Saturn (October 15th, 1997 to September 15th, 2017)

- **Vastly Updated Science on Saturn's Rings**
- **Incredible Science on Saturn's Moon Titan**
  - **Many Earth-Like Processes**
  - Liquid Rivers & Lakes of Ethane & Methane Over Frozen Water
  - Salty Brine Ocean Under Icy Crust
  - Liquid Water and Ammonia Ocean ~100km Below Frozen Crust
- **Likewise, Saturn's Moon Enceladus**
  - **Liquid Water Beneath its Icy, Snowy Crust**
  - Geologic Activity – Ice & Water Crystal Plumes at its South Pole



RTG Power Made this All Possible
SiGe Thermoelectric Materials



MARS SCIENCE LABORATORY (2012 to Current)

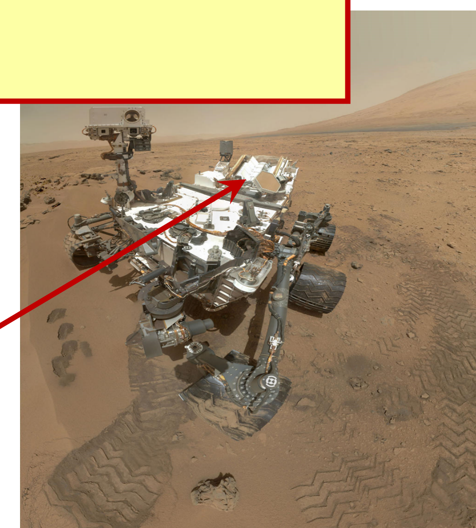
- Landed the Curiosity Rover on Mars in 2012 – Sky Crane
- About the Size of a Small Car (~2000 lbs)
- **Radioisotope-Driven Thermoelectric Generator (RTG) Used to Power Curiosity**

RTGs used successfully on 27 Missions since 1961

- **11 Planetary (Pioneer 10 & 11, Voyager 1 & 2, Galileo, Ulysses, Cassini, New Horizons)**
- **8 Earth Orbit (Transit, Nimbus, LES)**
- **5 Lunar Surface (Apollo ALSEP), 3 Mars Surface (Viking, MSL/Curiosity)**

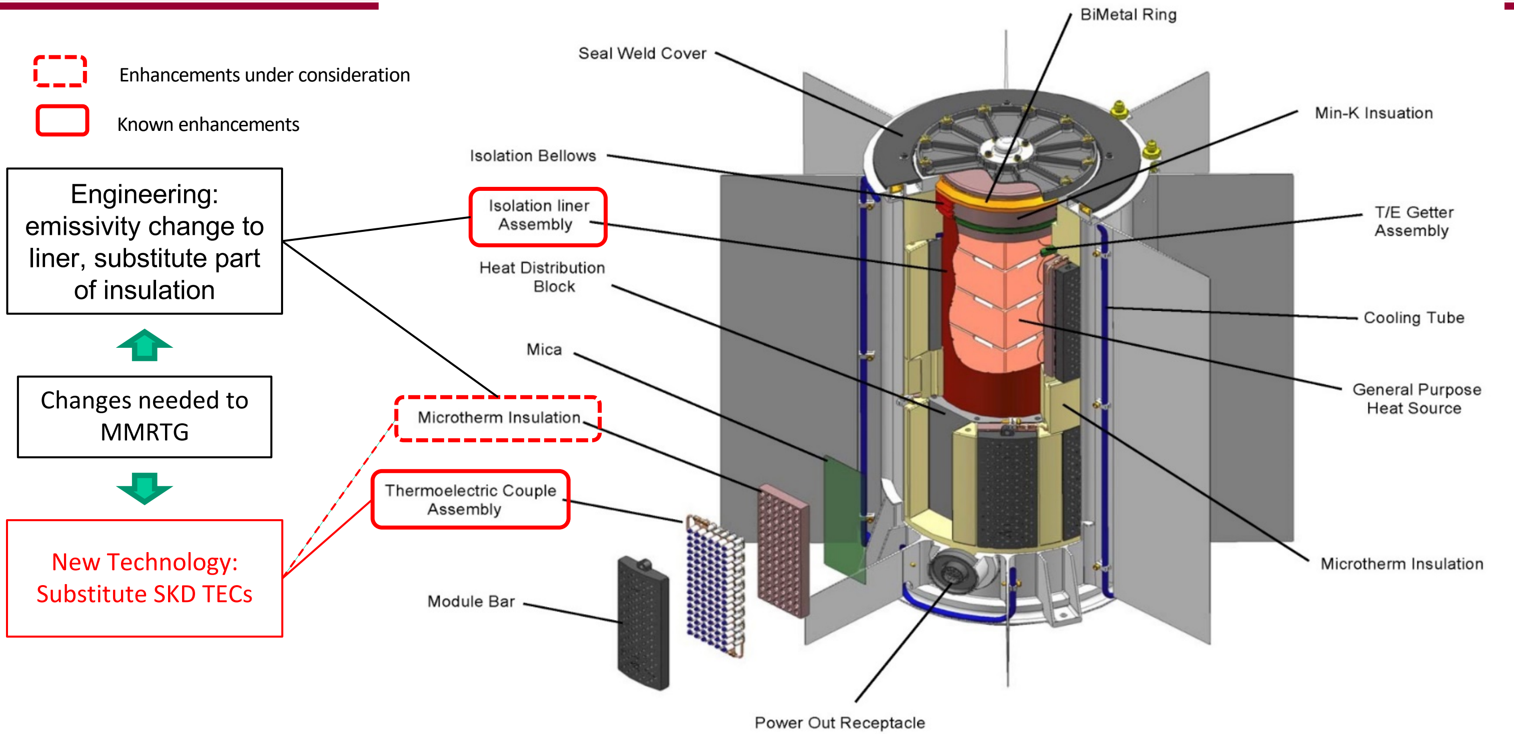
Destroyed

- Spent Last Year "Driving" from Landing Site to Mt. Sharp
  - 3-mile High Martian Mountain
  - Currently in the Foothills of Mt. Sharp
- Geology on Mars Similar to Earth



RTG Power Made this All Possible With TAGS, PbSnTe, and PbTe Thermoelectric Materials

What is being enhanced in the potential *eMMRTG*?



Replacing Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) couples with new Skutterudites (SKD) thermoelectric (TE) couples without significant design changes to the generator

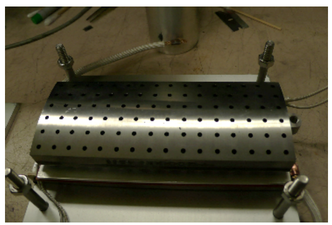
- SKD couples retrofit in the MMRTG TE module (no change in number of couples)
- Volume, mass, and external interfaces remain unchanged
- MMRTG's Multi-mission capability preserved while offering enhancement in power

A Boost in Conversion Efficiency with Low Risk Enhancements

Technology Transfer and Maturation + MMRTG Design Modifications = eMMRTG

Advanced SKD materials with higher performance and higher maximum operating temperature than MMRTG TE materials

Skutterudite (SKD) materials



Advanced SKD eMMRTG modules

SKD couples

10% increase in conversion efficiency over MMRTG couples

+

Operating temperature rises from 800K to 873K

Liner cross-section change boosts operating temperature

14% increase in conversion efficiency over MMRTG couples

→

The potential eMMRTG

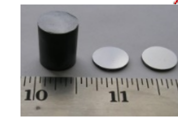
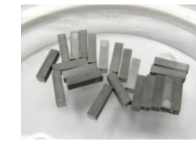
24% increase in conversion efficiency over MMRTG at beginning of life (BOL)

Phased Skutterudite Technology Maturation (STM) Program

- **Phase A key accomplishments**
  - Transferred JPL developed TE materials, metallized elements and TE module insulation production procedures to TESI
  - Demonstrated manufacturability and performance for SKD materials and elements
  - **Demonstrated initial manufacturability and performance for 1st iteration SKD couples**
  - Assessed thermal insulation options for modules
  - **Initiated life assessment of SKD materials, coupons, couples**

Successfully Passed Gate 1
Oct 2015

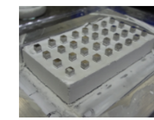
Phase A
~ 2 years

- **Phase B key objectives**
  - **Finalize couple and module design suppression at the end of Phase B couple development**
  - Further establish lifetime performance database through SKD materials, couples, and modules under nominal and accelerated testing conditions

Gate 2

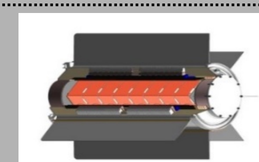
Phase B



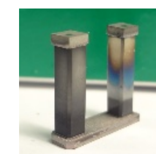
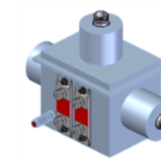
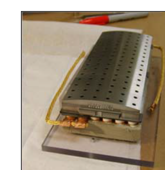

- **Phase C key objectives**
  - Design and demonstrate manufacturability and initial performance for SKD 48-couples modules
  - Finalize a lifetime performance database through SKD materials, coupons, couples, and modules under nominal and accelerated testing conditions
  - Develop a high reliability lifetime performance prediction (LPP)
  - Initiate verification of LPP through 48-couple module testing under nominal and accelerated testing conditions

Gate 3

Potential eMMRTG flight program development (DOE)



eMMRTG

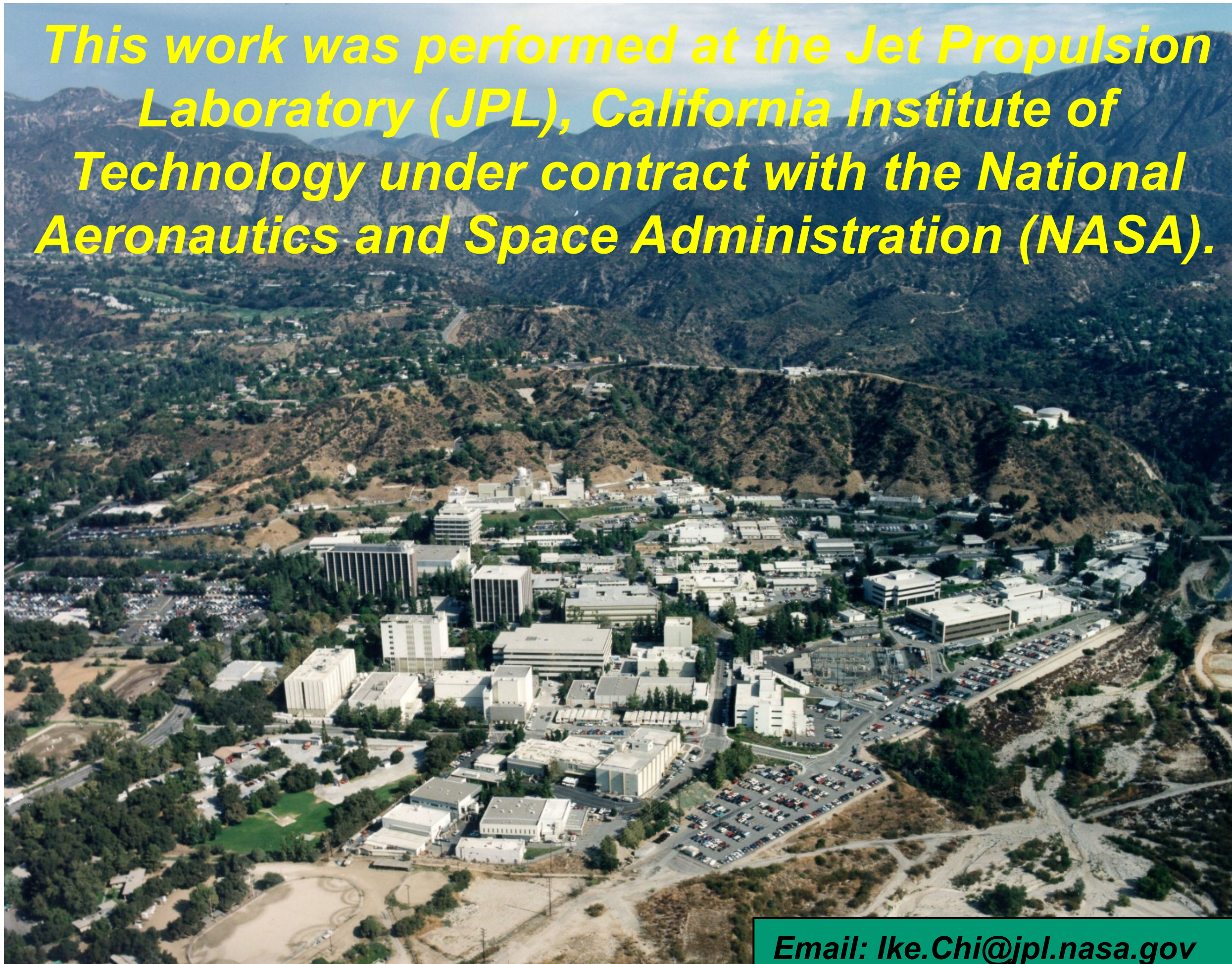




STM Team

- JPL (Lead), NASA Glenn Research Center (support), Department of Energy (DOE) (Guidance)
- Subcontractors: Teledyne Energy Systems Inc. (TESI)

Acknowledgments

This work was performed at the Jet Propulsion Laboratory (JPL), California Institute of Technology under contract with the National Aeronautics and Space Administration (NASA).



Email: Ike.Chi@jpl.nasa.gov