GEOTHERMAL CONCEPTS FOR LUNAR SURFACE SCIENCE PACKAGES?

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Surface Science System Concepts Objectives/Motivations

To provide inputs essential to the development of science requirements for surface system architecture for NASA SMD/ESMD OSEWG (Optimizing Science and Exploration Working Group) in support of the current exploration initiative efforts at JSC, LARC, and JPL

To explore non-conventional approaches and new technologies that minimize requirements (relative to conventional solar/battery system) but do not depend on the availability of plutonium-238.

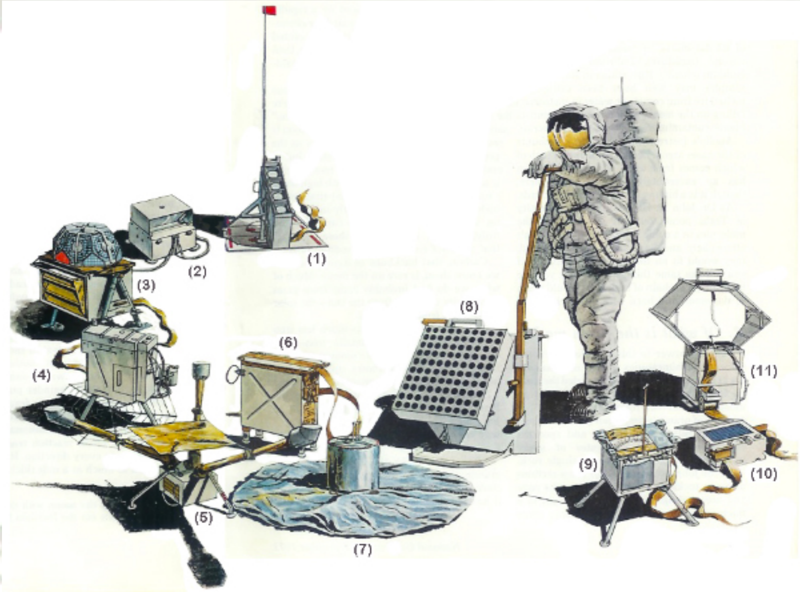
Geothermal: Explore potential geothermally-based designs for thermal support and/or science package power station that harness extreme conditions on the lunar surface, possibly the most challenging environment and yet not unlike most of the surface area in the solar system.

1) combined solar thermal/stirling geothermal power system

3) heat-pipe based thermal protection system

4) geothermalized regolith: innovative drilling, thermalizing materials, fluid injection technology

Experiment Time on the Moon



1) ASE Mortar Package Assembly
2) Heat Flow Experiment electronics box
3) Solar Wind Spectrometer
4) Suprathermal Ion Detector/Cold Cathode Ion Gauge
5) Lunar Surface Magnetometer
6) Charged Particle Lunar Environment
7) Passive Siesmic Experiment
8) Laser Ranging Retroreflector
9) Lunar Ejecta and Meteorites Experiment
10) Lunar Atmospheric Composition Experiment
11) Lunar Surface Gravimeter

Develop science packages serving multiple science constituencies and improved from ALSEP analogues:

<150 kg, < 0.5m, >5 years operation extending to night time with duty cycle

Present Day Challenges of Experiment Time

- Limited seismic network indicating Moon mostly solid, highly resonant, with potentially damaging quakes, diurnal and precessional activity cycles.
- Two shallow heat flow measurements indicated lunar heat flow 1/4-1/3 of earth, with apparent variations between major terranes and within diurnal and precessional cycles.
- Equatorial Retroreflectors measure geophysical state variations.

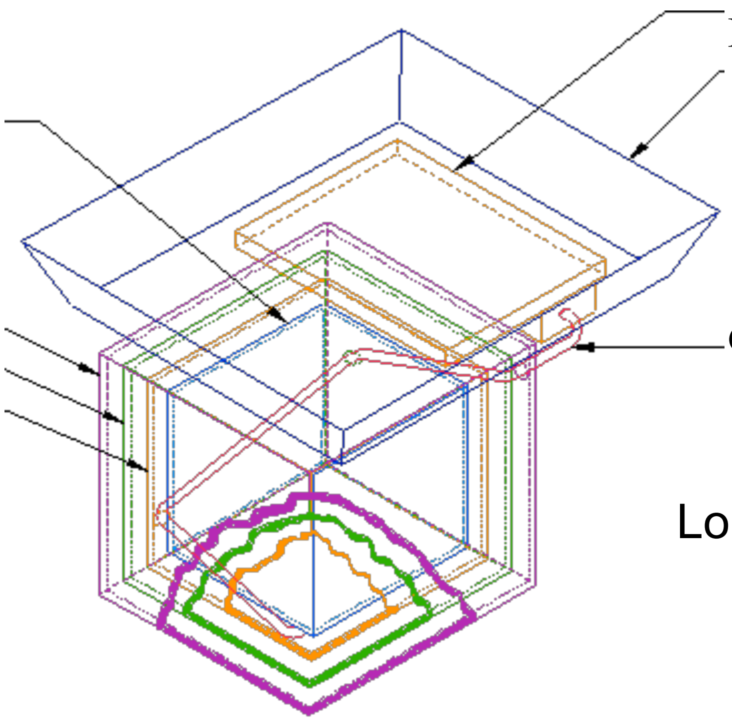
Need global network seismometers, >3m heat flow probes, reflectors to characterize interior activity, earthquake potential for long duration stays uncontaminated with local noise.

1. Magnetic and electric field measurements suggested systematic variations with diurnal and precessional cycles plus anomalies caused by direct interactions with plasma environment.
2. Short-term dayside measurements of solar wind, plasma, cosmic ray, atmosphere, charged particle, and atmospheric species environment.
3. Minimal characterization of dust behavior in context of fields and particles environment.

Need early (before and after occupation) measurements for full characterization interactions and long duration stays without local contamination.

TABLE 1. Reduction in mass and power for LEMS as new concepts were used

Design Regime	Conventional Electronics (pole)	Cold Electronics (pole)	Phase 1 Concept (pole)	Phase 1 Concept (diurnal)	Phase 2 Concept (diurnal)
Operational Limit C	-10	-40	-40	-40	-80
Survival Limit C	-20	-50	-50	-50	-100
Battery Mass kg	240	120	30	360	
Remaining Mass kg	260	260	70	75	
Total Mass kg	500	380	100	435	150kg (goal)
Minimum Power W	50	30	15	15	5 (goal)



Lorenz, 2008

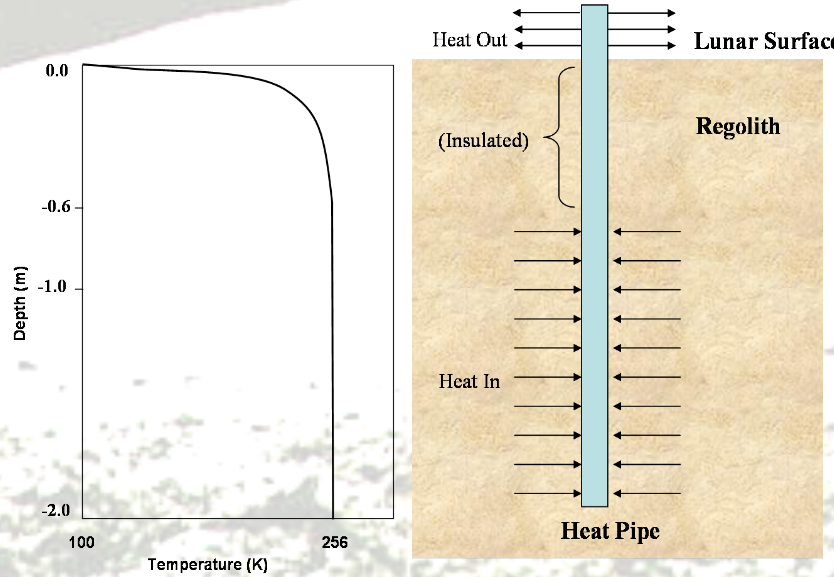
Thermal Control System Concept: Develop workable concept for thermal protection system for science packages by using resources in situ, harnessing relatively constant temperature of regolith >0.5 meter below surface representing 'heat reservoir" to be utilized for protection from cold during lunar night.

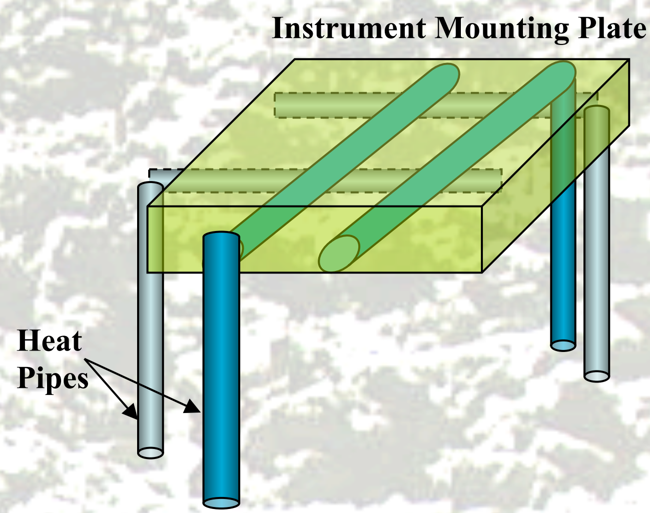
Use heat pipes to bring heat from the constant (latitude-dependent, 256K at equator, 100K at poles) temperature regolith that exists 0.5 meters below the lunar surface.

Heat pipes could be imbedded in the instrument mounting plate to maintain instruments temperature levels.

For unmodified regolith, the volume required to provide a constant power of 10W for the entire night time is about 0.62 m^3. The heat transport requirement (10W) is well within the current heat pipe capability, but the extremely low thermal conductivity and heat capacity of the regolith severely limits the rate at which heat can be removed.

Heat Pipe Heat Acquisition Concept for Lunar Surface





Thermal System Challenges

More than 10 heat pipes with diameters of 0.625″ and flanges of 1″ width deployed to 2 meters depth would be required to increase the rate of heat transfer with major implications for mass and EVA time.

The time and material expenditure required for astronauts to drill more than 10 holes to 2 meters depth would be problematic.

Thus, at least one order of magnitude increase in thermal conductivity and enhancement in heat capacity is required to make this concept feasible (1-2 holes).

The low thermal conductivity and heat capacity of the regolith result from the limited heat transfer between grains in a vacuum.

The regolith could be ‘thermalized’ by addition of high thermal conductivity/heat capacity substance (the ‘special sauce’) to increase contact between grains and thus allow heat transfer and yet not evaporate significantly over time.

Thermalizing Fluid: Identify candidates with appropriate range of thermal and physical properties over appropriate range of temperatures (from <-50°C to >150°C).

Two candidates with proper thermal (two or more order of magnitude greater thermal conductivity and heat capacity than regolith) and fluid properties.

1) AOS thermal grease 52030, a perfluorinated non-silicone zinc oxide compound with a very low melting point (-100°C) combined with high thermal conductivity and heat capacity, extremely low vapor pressure and high viscosity;

2) Ionic liquids (organic salts) with low melting point (down to -80°C) and negligible vapor pressure under high vacuum conditions.

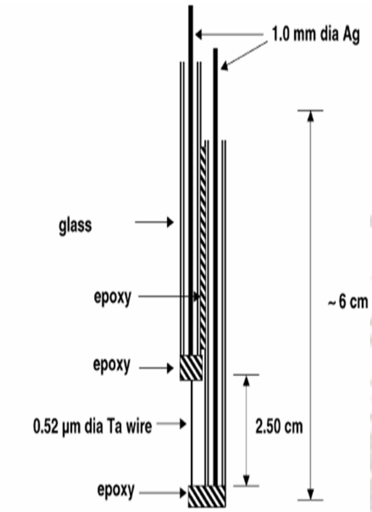
Such fluids would be injected during drilling to transform the area below the surface into a serviceable heat source/sink reservoir for geothermal use.

Thermal property	Moon	Thermal Grease
Thermal conductivity K	0.002 W/m-K (in situ) - 0.01 W/m-K (lab)	0.95 W/m-K
Specific heat C_p	670J/Kg-K	1130 J/kg-K
Density ρ	1.7-1.9 g/m^3	2
Specific Gravity	2.9-3.2 g/m^3	2.4

Thermalizing Fluid Challenges: Screen liquid and regolith mixtures for appropriate thermal and physical properties.

We are looking for optimum liquid/regolith ratio to increase thermal conductivity by 2 orders of magnitude. Multiple liquid-regolith mixtures (varying the nature of the thermal grease, ionic liquid, or ionic liquid combinations, as well as the percent composition with regolith) will be also be assessed in terms of melting point; anion complexation ability for possible complexation with inorganic salts present in regolith thus formation of complex mixtures, not only slurry/dispersed solid regolith; anion structure (acidic vs. neutral) for possible reactivity of acidic anions with regolith material and partial dissolution in slurry; cation structure (protonated vs. alkylated).

Rogers group (U of Alabama) has fabricated a Hot Wire probe to measure thermal conductivity, and are currently performing initial calibration and testing of the instrument. Initial screening did not indicate any visual dissolution or stable suspension of regolith samples in ionic liquids. The only visible observation is that for all ionic liquids tested, significant wetting of regolith is observed, boding well for this application.



Measuring Thermal Conductivity of Ionic Liquid

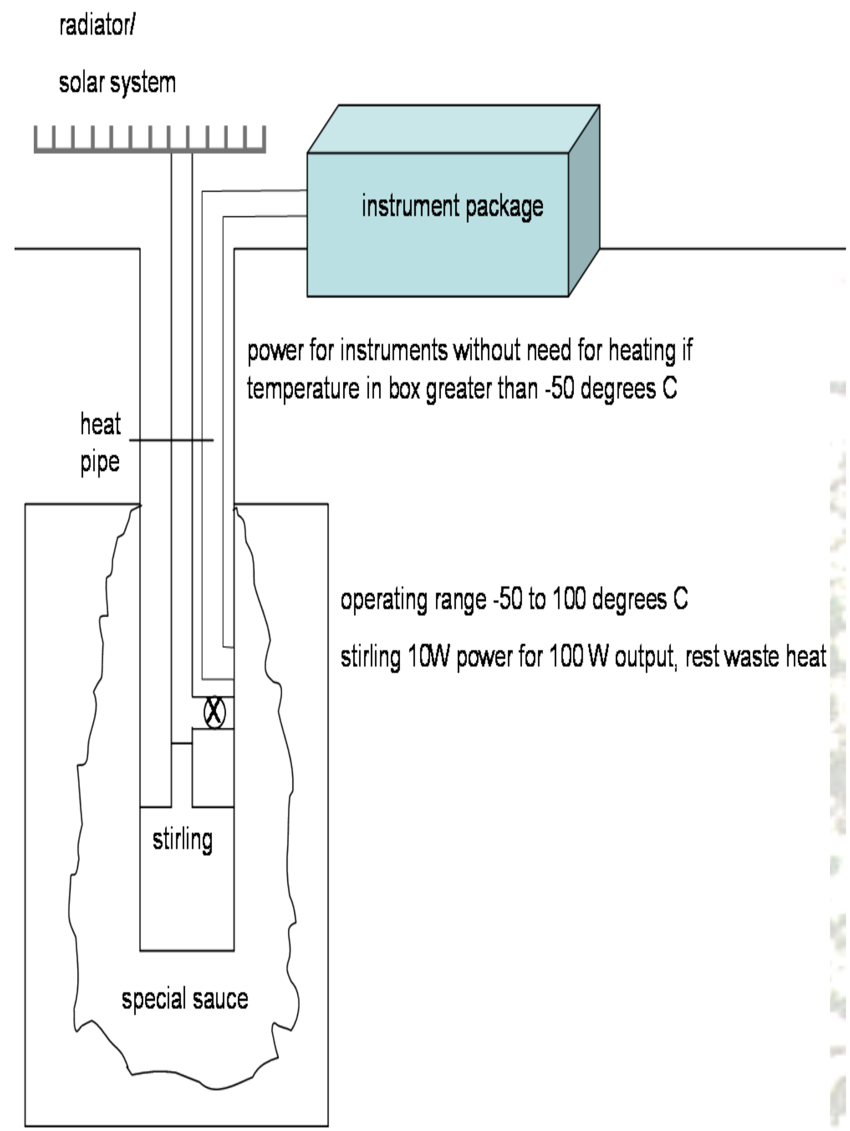
Geothermal Power System Concept: provide power for instrument packages at night using temperature differential between regolith and surface.

Use Solar thermal/Stirling geothermal power station to provide solar power for low duty cycle operation while trapping excess heat from surface systems in the thermalized regolith 'heat sink' during the day.

At night, the Stirling geothermal system harnesses that 'heat reservoir' to drive a sterling engine mechanism.

Currently the free piston Stirling engine is being developed for NASA's Advance Stirling Radioisotope Generator (ASRG), operating in a higher temperature regime. Our heat engine generates electrical power from the temperature differential between the relatively warm regolith and cold surface during lunar night.

Again, 1 to 2 orders of magnitude increase in thermal conductivity is required to make this concept feasible.



Stirling Geothermal System Challenges: Similar to Heat pipes.

Requires burial of one stirling engine attached via heat pipe/capillary pump loops assembly below 0.5 meters to be connected thermally to solar thermal system translating into need for reusable drilling assembly.

Requires comparable volume (0.65-0.75 m^3) of ‘thermalized’ regolith (at least one order of magnitude increase in thermal conductivity and enhancement in heat capacity) to act as thermal battery translating into need for deployment of ‘special sauce’.

The efficiency of the Stirling cycle is highly dependent on the operating temperature, so a computer model must track the net efficiency of the system through the lunar day/night cycle as a function of the local 3D temperature profile.

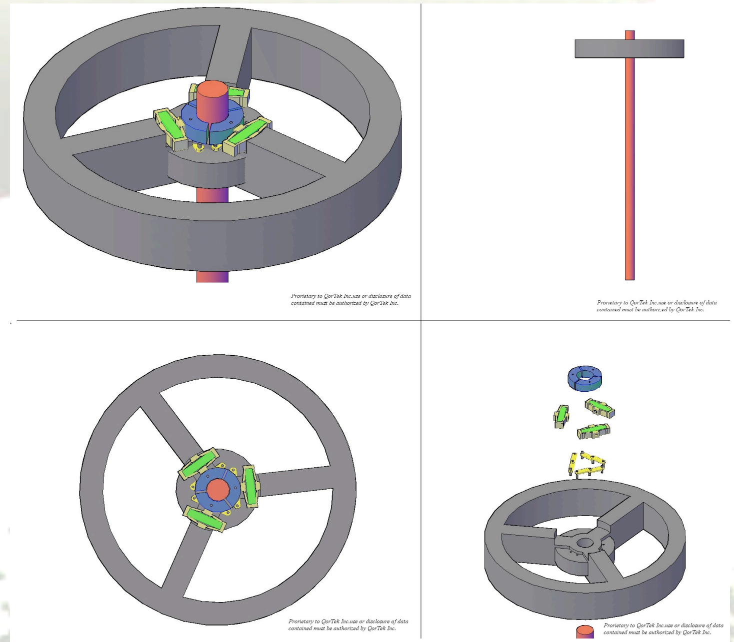
Additional mass:
Stirling Engine/Heat Pipe/Power and Thermal Connections Assembly: 15 kg
Special Sauce: 250-300 kg
Total Mass: 390 kg
Compare to: Total Mass 435 kg for diurnal cold temperature solar battery system.

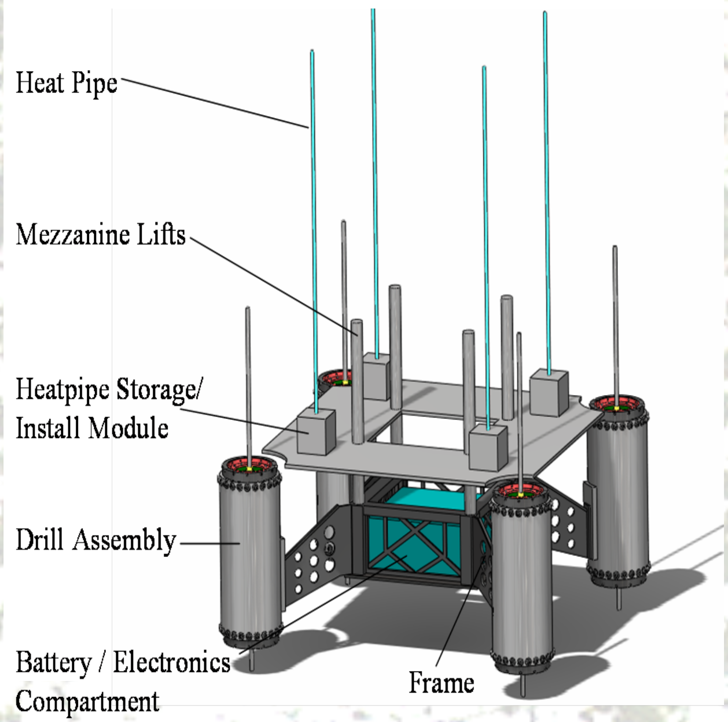
For 0.7 m^3 of lunar soil with average bulk density (ρ) of 1.7 g/cm^3, and average specific gravity (G) relative to water of 3.1 g/cm^3 below 0.5 meters, where $\rho = G(1-n)$ the average porosity (by volume) (n) is 25%. The mass pore-filling AOS 52030 required to fill that volume would be approximately 300 kg, or 250 kg if the overall volume is adjusted downward for its doubled heat capacity (Lunar Sourcebook).

Reusable Drill Assembly Concept: for drilling, deploying heat pipes and injecting thermalizing liquids under pressure.

Qortek-designed innovative low power, readily portable and deployable, multi-functional, piezo-electric flywheel-driven, high torque drill assembly enabling multiple drilling in a trilaterally stable configuration. Additional core sampling capability envisioned.

The drilling/deployment/injection system must be easily ported and assembled, enable multiple core drilling in a trilaterally stable configuration, and be multi-functional, enabling emplacement of heat flow enhancing liquids as to ensure high performance thermoelectric power conversion made available to the mission during the night side operations as well as core sampling.





Summary and Conclusions

With an alternative approach using available technology, we have been able to reduce mass requirements for ‘typical’ science package deployed near poles by factor of 5. Incorporation of ULT/ULP technology in phase 2 should allow similar or greater optimization anywhere on Moon.

This very preliminary study on the use of in situ regolith for thermal protection or geothermal power stations indicates this approach may be feasible on the basis of potential reusability and/or when compared to current solar battery systems.

Key materials/technologies of interest and requiring development include:

Thermal and physical properties of Ionic liquids/regolith or thermal grease/regolith mixtures as a function of temperature and pressure

Low power piezo-electric flywheel drilling concepts

Heat Pipe Technology

Stirling Engines for lower temperature range applications backup slides for further discussion

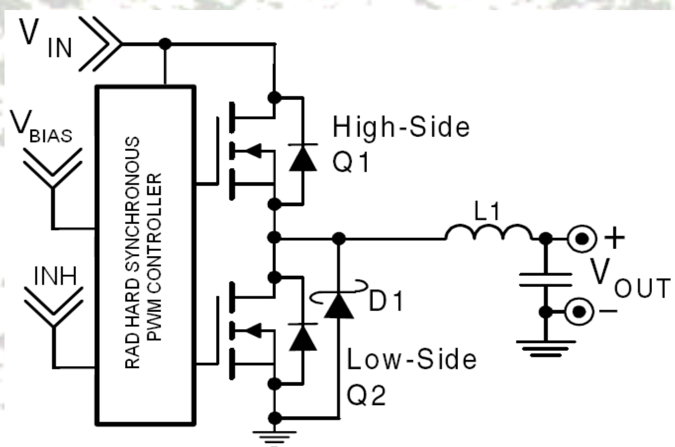
ULP Power Supply required for Ultra Low Power

Ultra Low Temperature Electronics, minimizing power and thermal requirements, take advantage of drastically reduced voltage thresholds to reduce power required for processors.

Traditional power processing circuits rely on diodes to rectify high frequency AC voltage waveforms to produce the output voltage desired. The voltage that the ULP requires (0.5V) less than a diode drop driving the efficiency if package designed with traditional approach to well below 40%, reducing any gains made by ULP incorporation.

Workable solution to provide power reliably and efficiently down to such small voltage levels for ULP processor: a power processing scheme that eliminates the forward diode drops during the rectification process is proposed. Methodology of power processing called 'synchronous rectification' commonly used on computer processor ICs down to 1.5V.

The Lunar Package power processing will require Radiation Hardened circuitry and is required to produce voltage levels at one-third of the 1.5V level. Anticipated that a circuit similar to the one below will produce stable voltages down to 0.5V at an efficiency of approximately 85%.



E. Young, GSFC, 2008

Technologies critical for Science Goals/Objectives Requiring Longer Duration (5-10 years) supporting Science Instruments/Packages/Tools on

Robotic Precursors

Astronaut Deployed Packages during human occupation

Experiments on surface between or subsequent to human occupation

Including Ultra Low Temperature (ULT) and Ultra Low Power (ULP) versions of components

- electronics (digital and analog already proven at chip level for ASICs FPGAs
- Batteries efficient and surviving at lower temperatures
- power supplies operating at lower temperatures and at lower power
- systematic conversion all components to ult and ulp
- these technologies applicable mercury to asteroid belt ((solar cell/battery systems)
- critical without assured availability of pu238 for inner solar system

Ultra Low Temperature/Ultra Low Power Electronics (Digital and Analog)

Digital Developed at GSFC and through partnerships with the University of Idaho (Maki and Yeh, 2003), Department of Defense (DoD), National Reconnaissance Office (NRO).

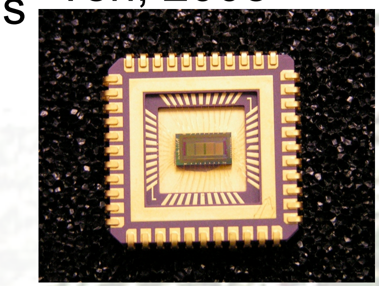
ULT/ULP chips demonstrated orders of magnitude savings in power consumption and thermal tolerance (Maki and Yeh, 2003) on CULPRiT (CMOS Ultra-low Power Radiation Tolerant) technology flown on NASA's ST5 90 day mission, 2006.

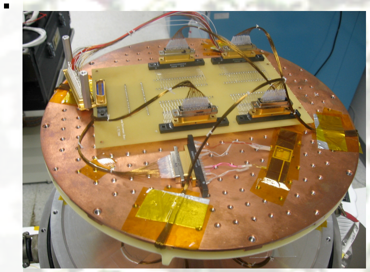
The ULP processor scheme reduce the overall power requirements, reducing size of the solar power and energy storage systems, the need for active heaters and more temperature sensitive electrolytic capacitors.

The power requirements for ULP processor output efficiency less than 30% with traditional power conversion techniques (0.5V) , so new distribution schemes/ power converter techniques needed.

Models for CMOS circuit fabrication components in extremely high or low temperatures being developed at GSFC, allowing the incorporation of these components in ULT/ULP in a growing number of analog and mixed signal electronics in either FPGAs, ASICS, or Structured ASICS, combining the advantages of ASICS but at the lower cost of FPGAs.

Yeh, 2008





Cooper, 2008

Micro-Batteries, Power Supplies operating at ULT/ULP

Haven't yet fully explored how much we can mitigate heat loss by packaging micro-batteries with individual instruments. Will require much more sophisticated power management.

Alternative battery technology potentially capable of operating at ultra-low temperatures becoming available for micro-battery applications (West et al, 2000).

More efficient harnessing of solar energy

Thing solar film, extremely thin film of amorphous silicon, 40 times more efficient than crystalline silicon used in traditional panels, vapor deposited on flexible thermally stable support medium.

Replacement of solar panels with thin film solar cells, developed under NASA's auspices (NASA Spinoff, 2006; Dickman et al, 2008), could result in a considerable mass savings because of the inherently higher efficiency of the film and its ability to 'wrap' without structural support.

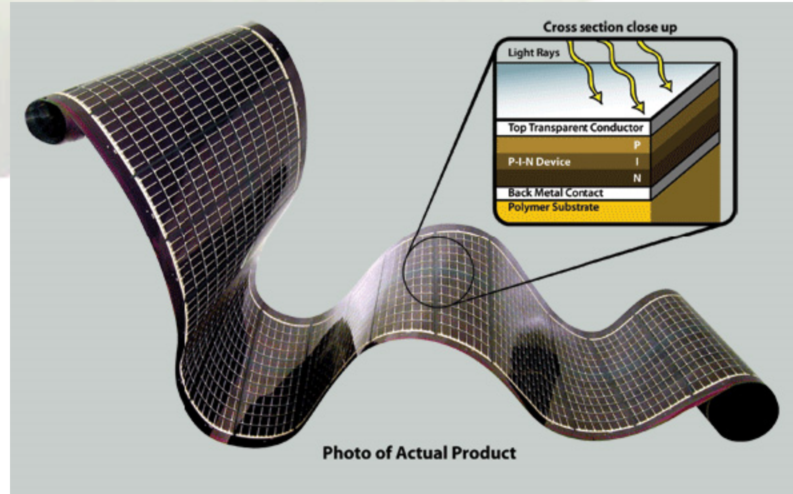
The Nantenna technology which is finally coming of age harnesses mid-Infrared energy to produce electricity even more efficiently (Kotter et al, 2008).

Thin film solar cells on flexible media

Combine gas deposition amorphous silicon on flexible substrate (in domestic use for convenience but still not very efficient)

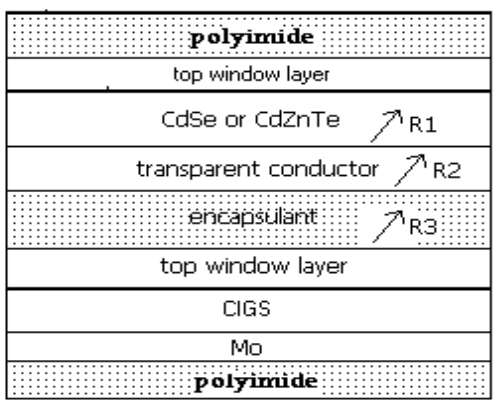
WITH multijunction cell stacked and having bandgaps tuned to convert spectrum passing from upper cells to lower cells

to produce solar cell system with competitive (25%) efficiency plus lower volume and mass.

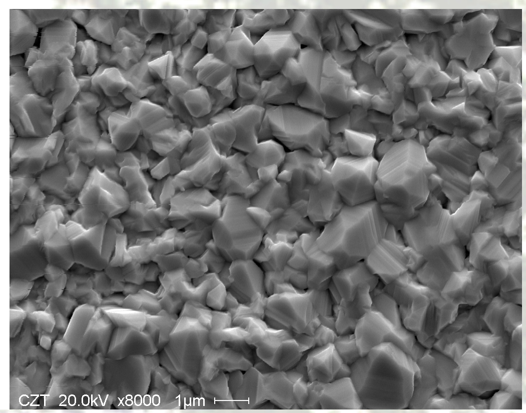


stacked cell concept

light

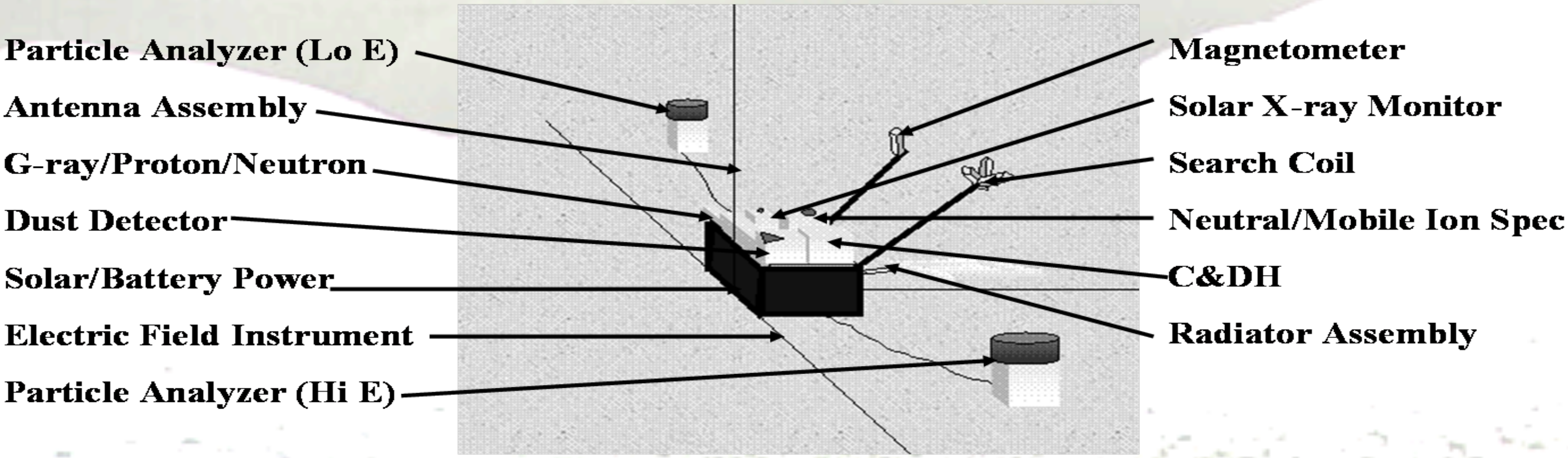


CZT vapor deposited tunable bandgap material



Dickman et al, NASA TM-2004-212554

Automated Lunar Environmental Monitoring Station Concept



Automated Lunar Geophysical Station Concept