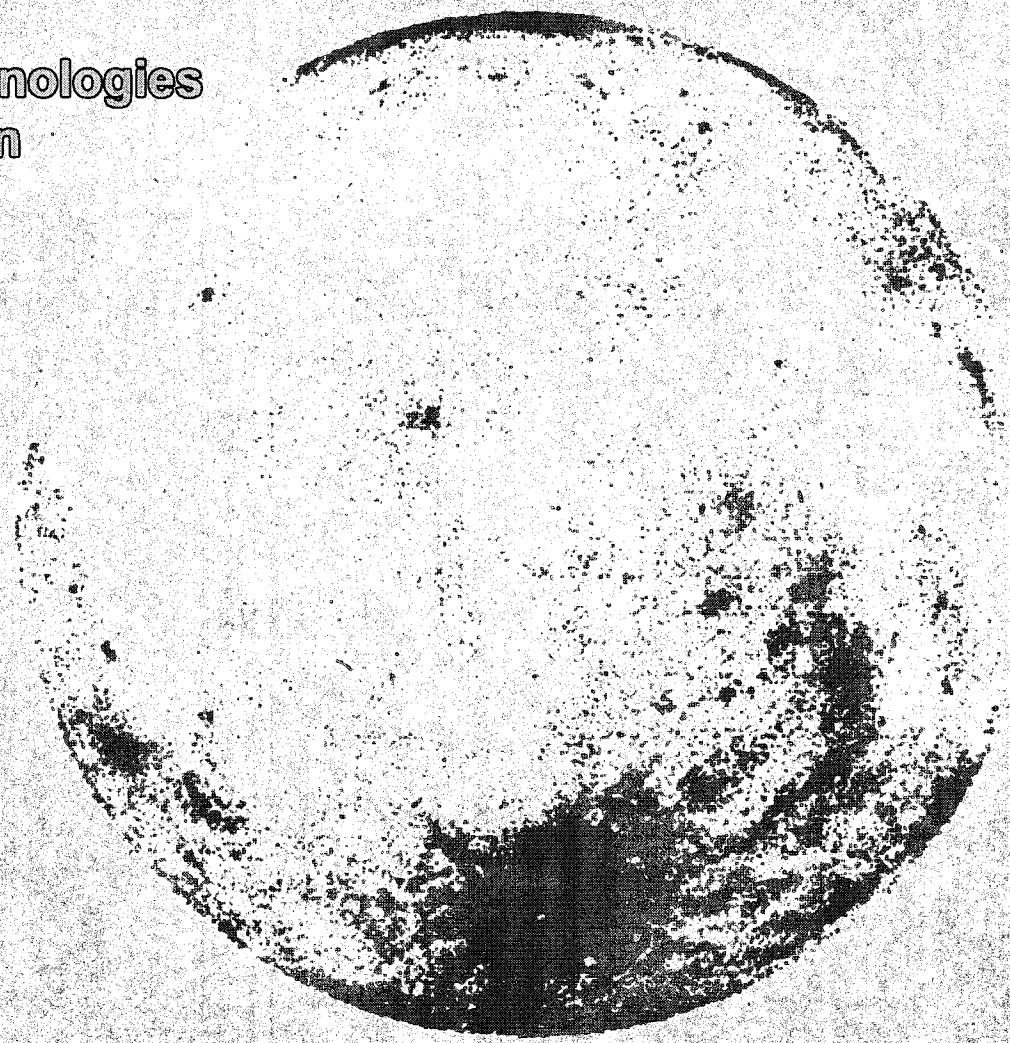
Extreme Environment Technologies for In-situ Lunar Exploration



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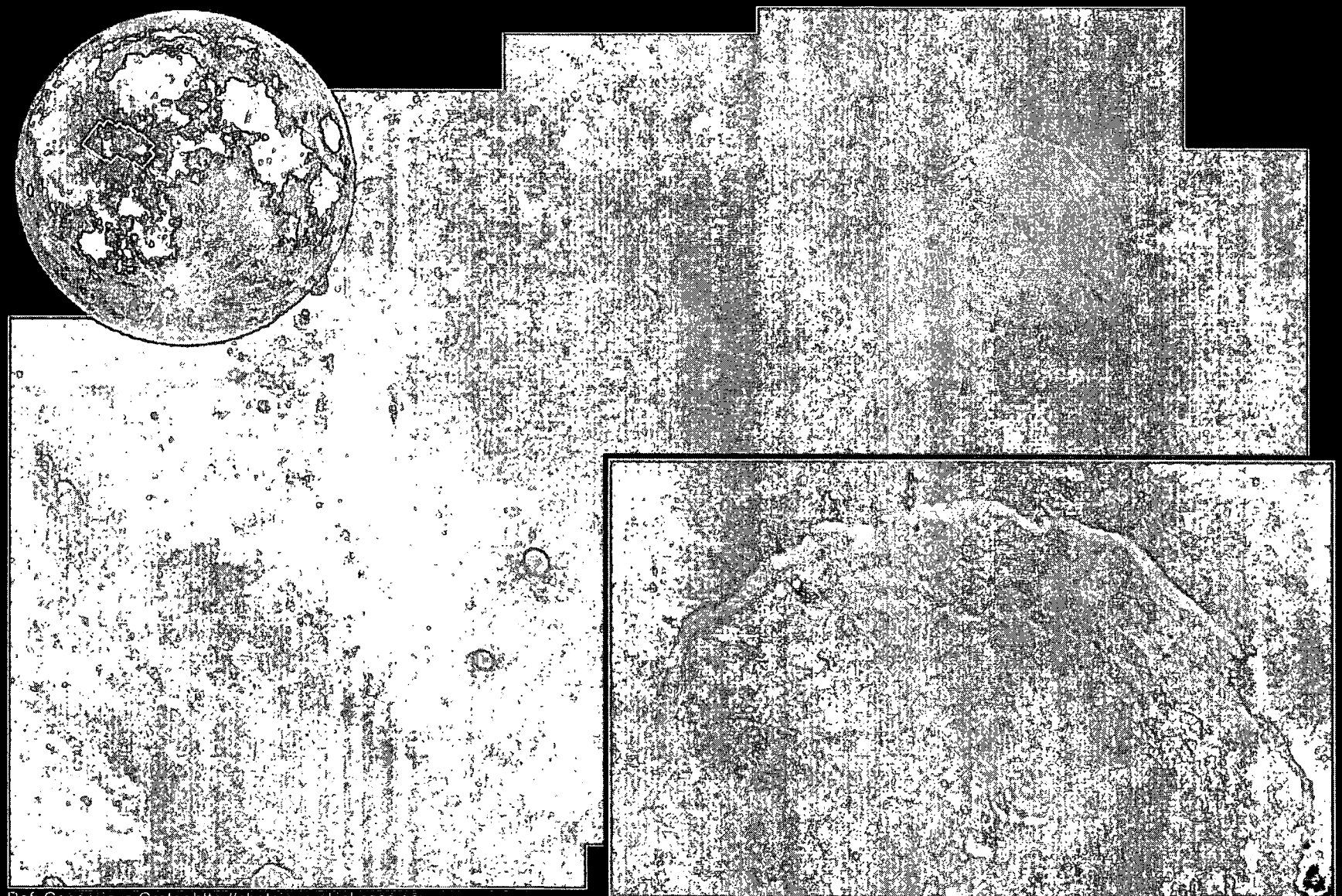
Any opinions, findings, and conclusions or recommendations expressed here are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.

Ref: Apollo 17 Moon panorama

Overview

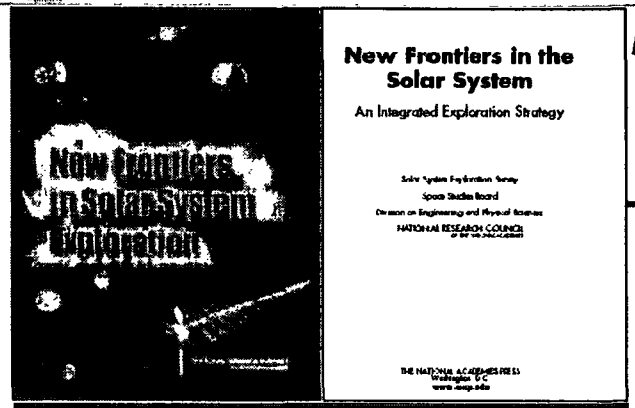
- Introduction
  - NASA's SSE Roadmap
  - Extreme environments
- Technologies for Lunar Extreme Environments
  - Systems architectures
  - Key Lunar EE technologies
- Conclusions

Introduction

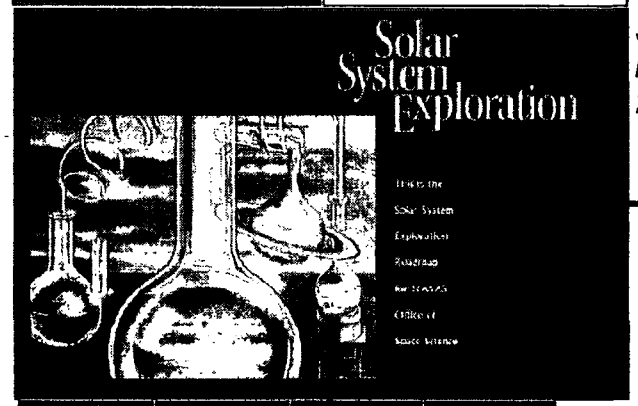


Ref: Copernicus Crater http://photojournal.jpl.nasa.gov

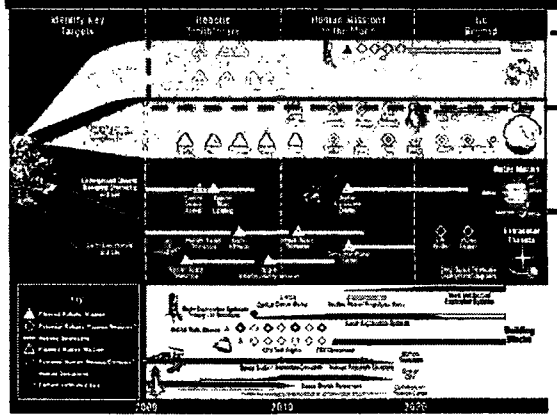
Roadmap Foundation Materials & NASA's 2006 Solar System Exploration Roadmap



NRC DS



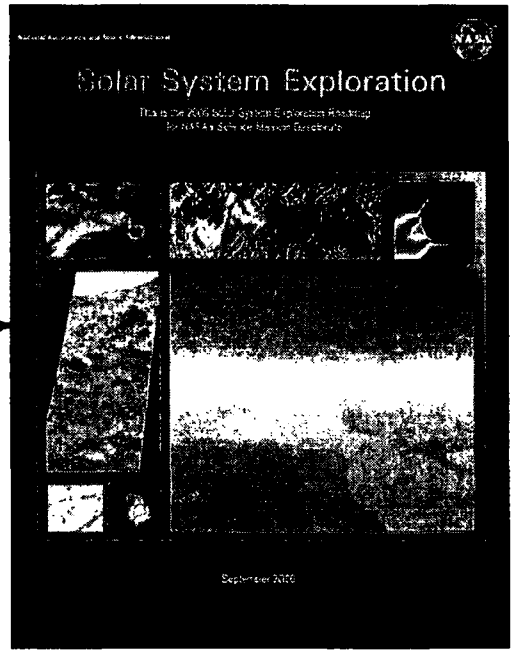
SSE RM 2003



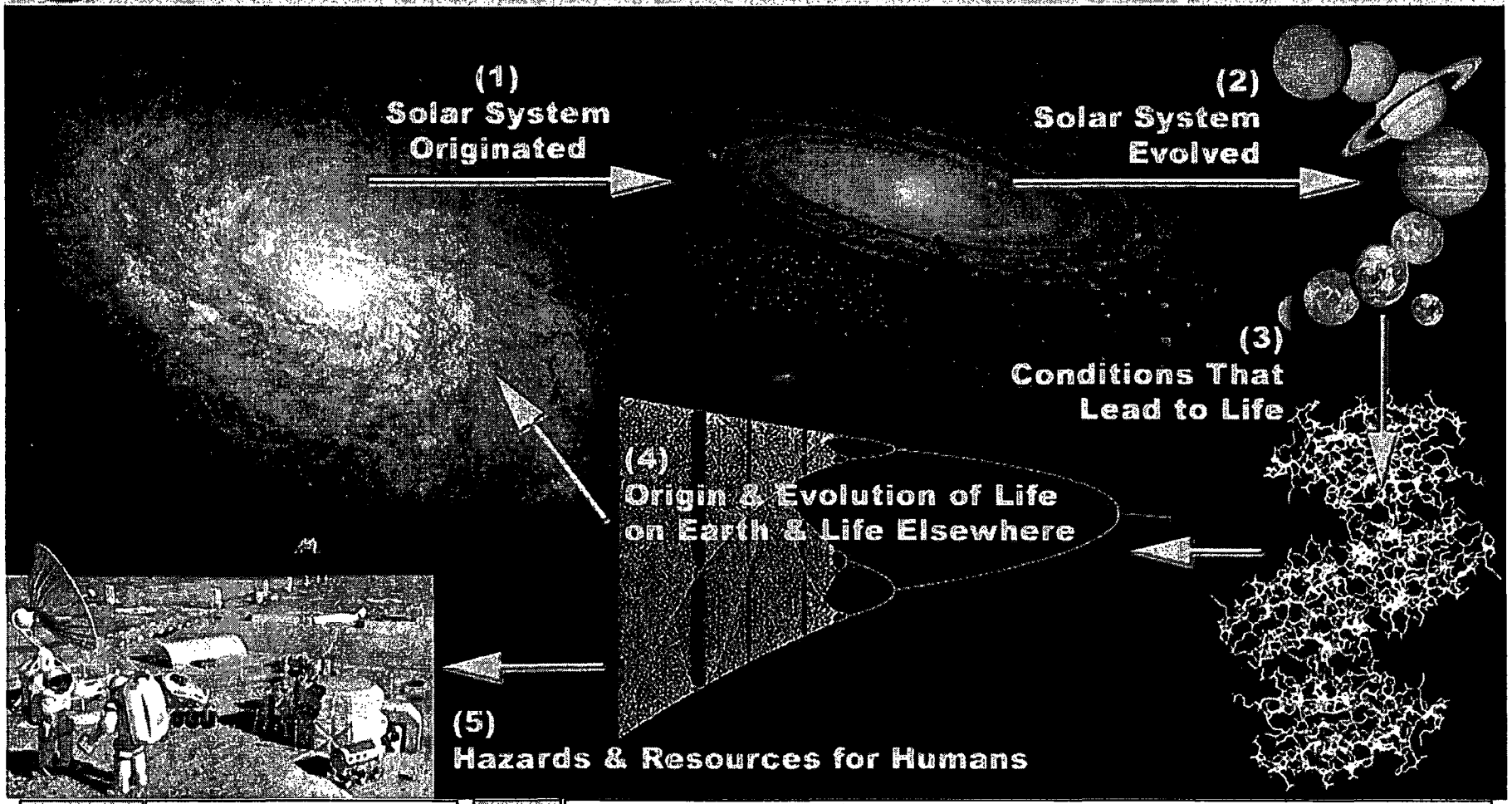
Lunar Pathway

Vision for Space Exploration 2004

- New Frontiers in the Solar System – NRC Decadal Survey of 2003
  - Science strategy; First Decade - recommended mission set; Second Decade – mission options; Technology needs
- Solar System Exploration Roadmap of 2003
  - Accepted most but not all Decadal Survey recommendations
- Vision for Space Exploration – 2004
- Design Reference Missions set
  - reflecting an updated assessment of the range of mission candidates
- NASA's 2006 SSE Roadmap



Science: Solar System Roadmap Investigation Pathways



Underlying Theme: Habitability

- Habitability of worlds
- Architecture of systems
- Hazards to Earth

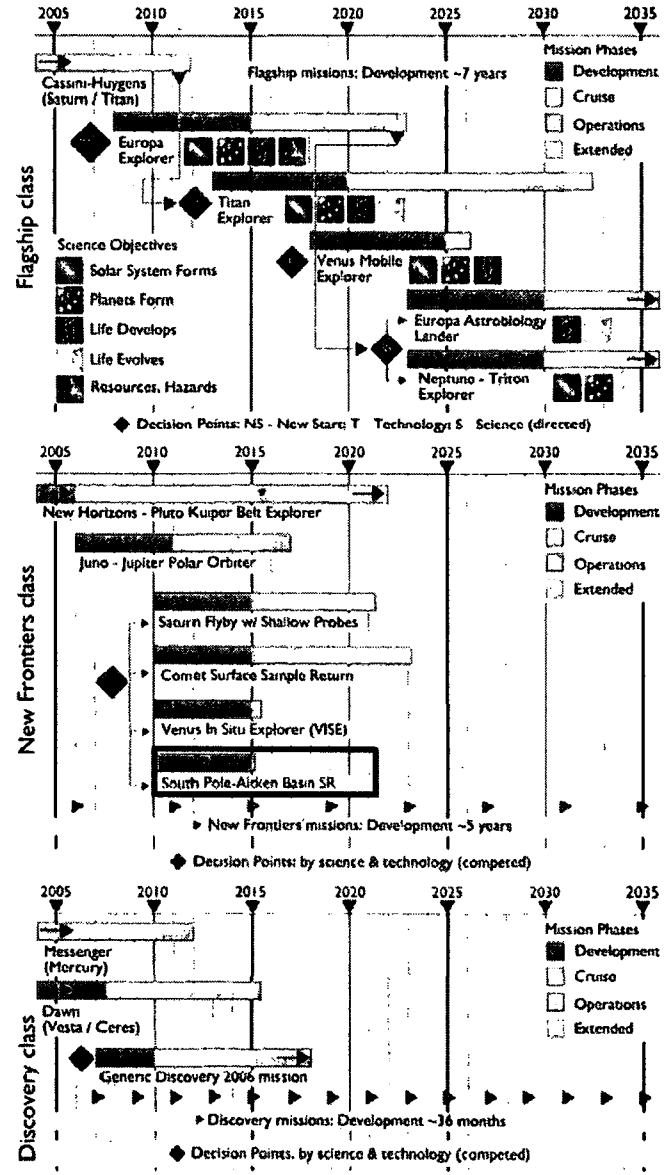
Scientific Questions

- How did the Sun's family and minor bodies originate?
- How did the Solar System evolve to its current diverse state?
- What are the characteristics of the Solar System the lead to the origin of life?
- How did life begin and evolve on Earth and has it evolve elsewhere in the SS?
- What are the hazards and resources in the Solar System environment that will affect the extension of human presence in space?

Proposed Missions by the SSE Roadmap Team

Recommended 3 mission classes:

- **Flagship class**
  - ~2 per decade
  - Directed
  - Cost cap: ~$1.5-3B
- **New Frontiers class**
  - ~3-4 per decade
  - Competed – PI lead
  - Cost cap: ~$750M
- **Discovery class**
  - ~4-7 per decade
  - Competed – PI lead
  - Cost cap: ~$450M



Reference:
SSE Roadmap Team, "Solar System Exploration; This is the Solar System Exploration Roadmap for NASA's Science Mission Directorate," National Aeronautics and Space Administration, Science Mission Directorate, Planetary Science Division, Report Number: JPL D-35618, September 15, 2006; Website: solarsystem.nasa.gov

Science Traceability Matrix

- Science Objectives are mapped against the proposed mission concepts in each mission class
  - Discovery missions address only a few science objectives
  - New Frontiers are broader, but
  - **Flagship class missions are REQUIRED** to address certain complex science objectives that smaller missions can't address
- Therefore, we need a balanced program that includes Discovery, New Frontiers **AND Flagship class** missions!
- Some of these missions target destinations with **extreme environments**, and may require enabling and/or enhancing technologies

Major Questions	R&A		Discovery				New Frontiers						Flagship (Small/Large)							
Objectives	Expt.†	Theory	SB	Moon	Venus	Mercury	NH	Juno	SPABSR	VISL	CSSR	SP	C/H	EE	TE	VME	EAL	NTE	*CCSR**	*VSSR**
How did the Sun's family of planets and minor bodies originate?																				
Understand the initial stages of planetary and satellite formation	●	●	●	●	△	△	●	●	●		△	●	△	△	△	△		●	●	●
Study the processes that determine the original characteristics of bodies in the Solar System	●	●	●	●		△	△	●	△		●	●	△	△	△			●	●	●
How did the Solar System evolve to its current diverse state?																				
Determine how the processes that shape planetary bodies operate and interact	△	△	△	△	△	△	△	△	△	△	△	△	●	●	●	●	●	●	●	●
Understand why the terrestrial planets are so different from one another	△	△			●	△			△	●						●				●
Learn what our Solar System can tell us about extrasolar planetary systems	△	△					△	△				△	●	△	△	●		△		●
What are the characteristics of the Solar System that led to the origin of life?																				
Determine the nature, history and distribution of volatile and organic compounds in the Solar System	△	△	△				●	●		△	●	●	●	●	●	●	●	●	●	●
Determine evidence for a past ocean on the surface of Venus	△	△			△					△						●				●
Identify the habitable zones in the outer Solar System	△	△											●	●	●		●	●		
How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?																				
Identify the sources of simple chemicals important to prebiotic evolution and the emergence of life	●	△	△				△						●	△	●		●	△	●	
Evidence for life on Europa, Enceladus, and Titan	△	△											△	△	●		●			
Evidence for past life on Venus	△	△														△				●
Study Earth's geologic and biologic record to determine the historical relationship between Earth and its biosphere	●	△																		
Identify environmental hazards and resources enabling human presence in space																				
Determine the inventory and dynamics of objects that may pose an impact hazard to Earth	●	△	●				△													
Inventory and characterize planetary resources that can sustain and protect human explorers	△	△	●						△		●									

Convention ● Major or Unique Contribution △ Significant Contribution

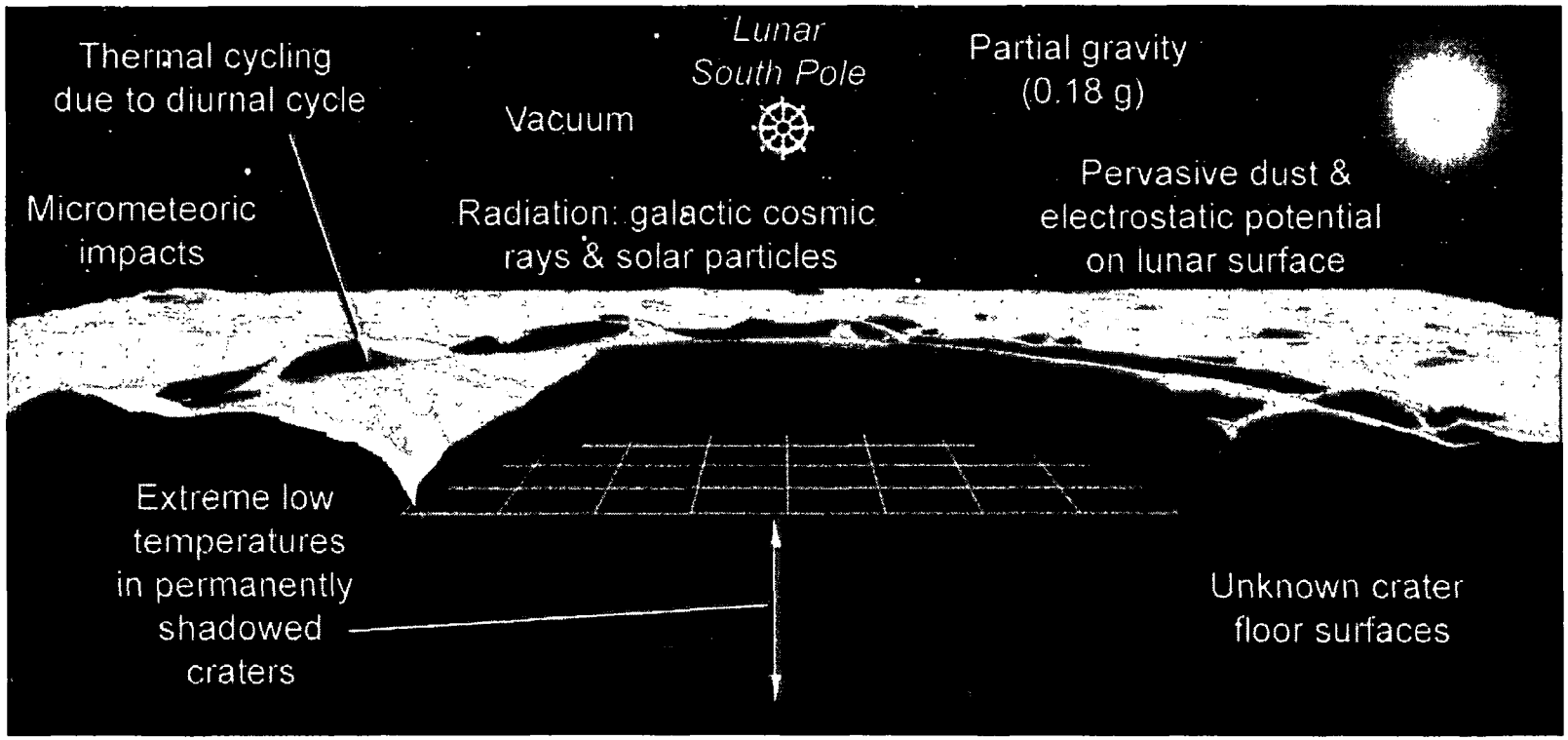
SB – small bodies NH – New Horizons SPABSR – South Pole Aitken Basin Sample Return VISL – Venus In Situ Explorer
CSSR – Comet Surface Sample Return SP – Saturn Flyby with Shallow Probes C/H – Cassini Huygens, EE – Europa Explorer
TE – Titan / Enceladus Exp VME – Venus Mobile Exp EAL – Europa Astrobiology Lander NTE – Neptune Triton Explorer
CCSR – Cryogenic Comet Surface Sample Return VSSR – Venus Surface Sample Return – *beyond the 5 types of Flagship missions*
† – *Expt includes ground and space based observatories with a range of NASA facilities including the Hubble and Spitzer Space Telescopes and in the next decade the proposed James Webb Space Telescope*

Extreme Environment Conditions on the Moon

- **Surface temperature:** Min: -233°C / Max: +197°C - Average: +31°C
- **Radiation:** ~10 rad/year on Moon + crossing the Van Allen radiation belts

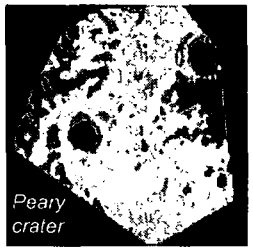
- **Thermal-cycling:** -233°C (min) to +123°C (max); fortnightly
- **Physical corrosion:** Dust + electrostatic charging

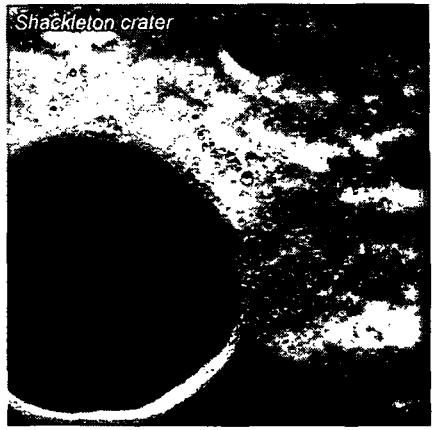
- **Re-entry heat flux:** ~1.2 to 1.6 kW/cm^2 (PICA TPS) for Earth return
- **Deceleration:** ~40 g experienced by Stardust; ~5 g for human missions



Lunar Mission Architectures & Targets

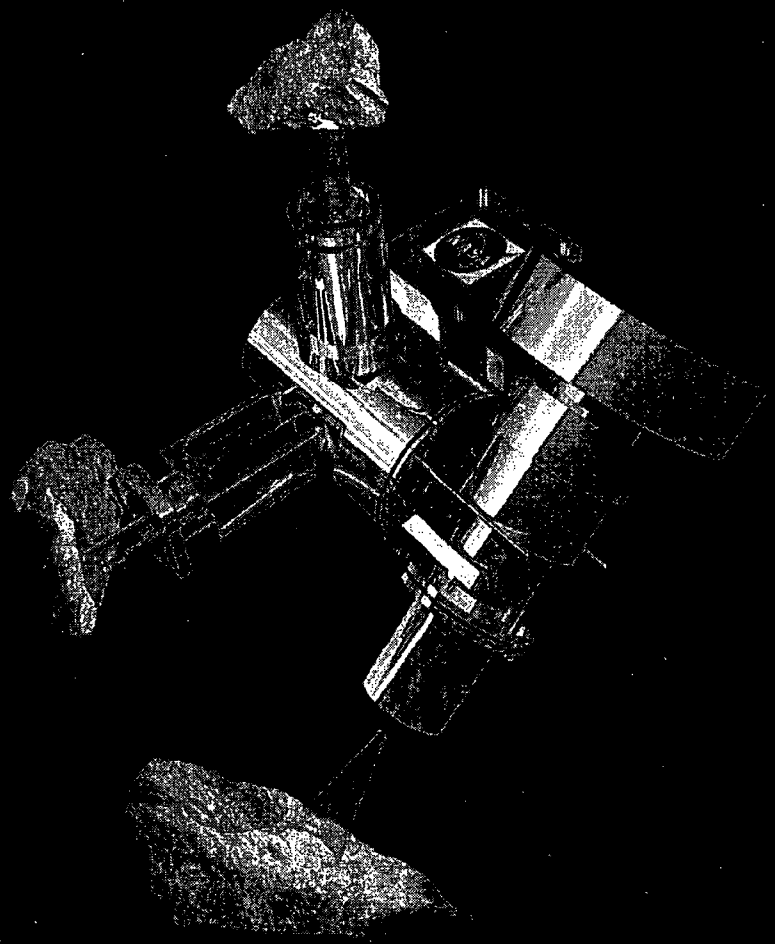
- **Sortie missions** building up man–made surface elements on the Moon could also pose potential environmental hazards.
  - Thus, the design and development of lunar technologies and habitats must **respond** effectively **to these extreme environments related threats;**
  - Potentially **making lunar architectures complex and challenging**.

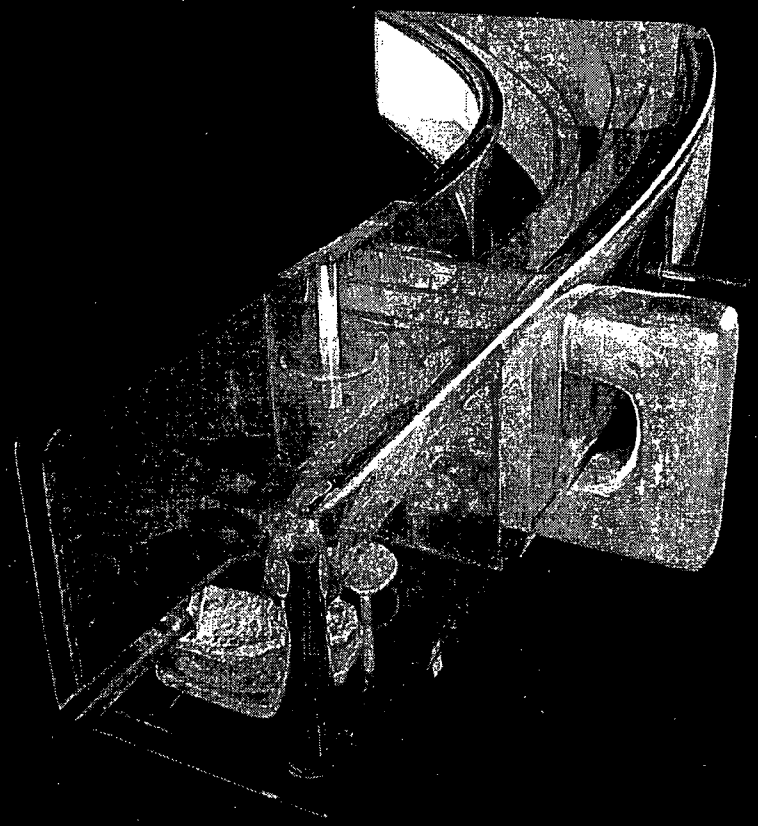




- Lunar architectures could target
  - **Equatorial regions:**
    - **Diurnal cycle** → extreme thermal cycling,
    - Surface temperature could rise to +197°C at lunar "noons"
    - Could sink below −233°C at nights.
  - **Polar craters:**
    - **Permanently shadowed** craters → robotic missions for **potential ISRU;**
    - *Assuming that these craters could hold a significant amount of easily accessible water ice, convertible into resources for future missions.*
  - **Permanently or near–permanently sunlit crater rims:**
    - Such as those of the polar Shackleton and Peary craters;
    - Could be chosen for their **proximity to possible in situ resources** at the bottom of the craters, **combined with solar availability** for human bases

Extreme Environments Technologies

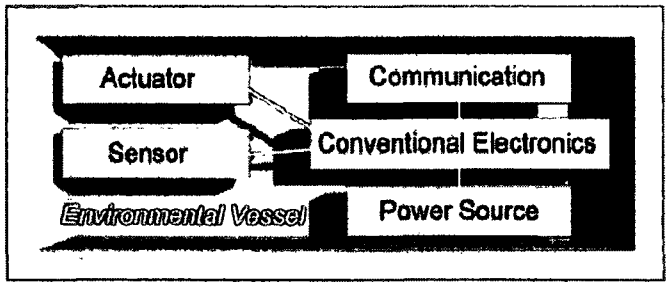




System Architectures

Protection Systems

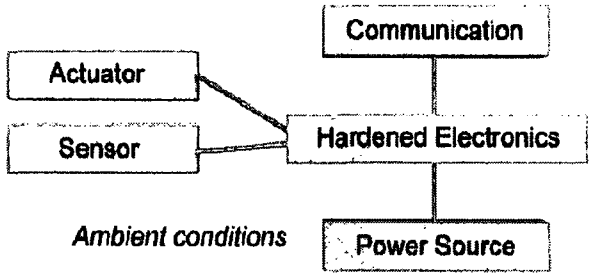
Use conventional components; Develop protection systems (Thermal vessel, pressure vessel, radiation shielding etc.)



Impractical for planned missions

Component Hardening

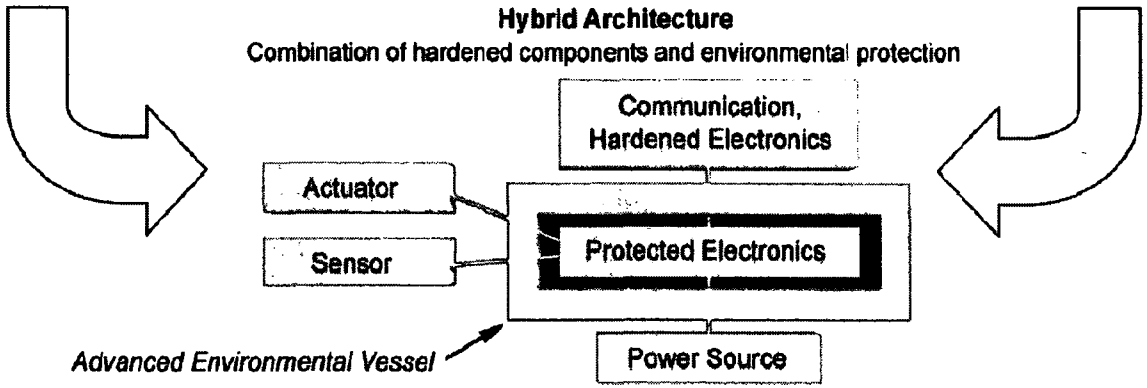
Develop technologies tolerant of extreme environments



Prohibitively expensive for some technologies

Hybrid Architecture

Combination of hardened components and environmental protection



Requires development of innovative architectures

Systems architectures for extreme environments can be categorized by:
- the **isolation** of sensitive materials from hazardous conditions;
- the development of sensitive materials, **tolerant** to hazardous conditions;
- and an appropriate **combination of isolation and tolerance**.

Key Extreme Environment Technologies

Technology needs could be categorized into three general areas:

1. **Environmental protection** technologies providing isolation from extreme environments;
2. **Environmental tolerance** for exposed components or systems;
3. **Operations in extreme environments**.

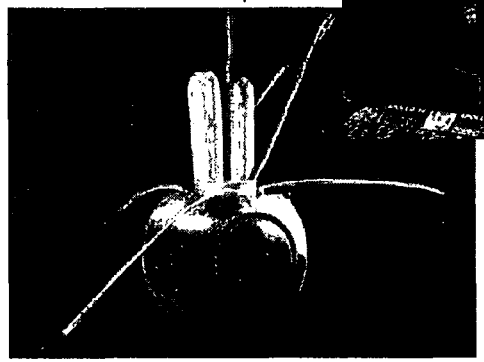
- Protection systems:
  - Hypervelocity entry (Earth return)
  - Temperature mitigation
- Thermal-cycling
- Low-T electronics
- Low-T power storage & generation
- Low-T mechanisms & sample acquisition
- Low-T surface mobility

Protection Systems:
Hypervelocity Entry – for Earth Sample Return

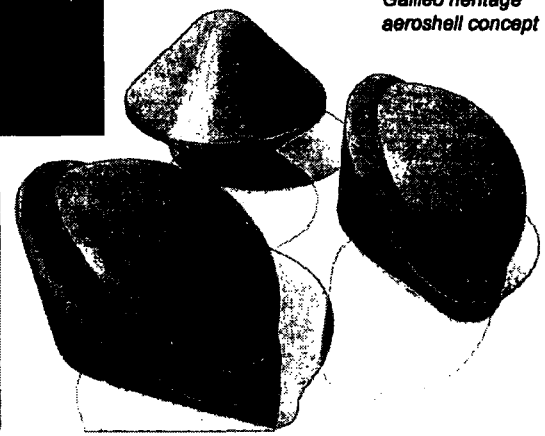
- The **Thermal Protection System** (TPS) protects (insulates) a body from the extreme heating encountered during hypersonic flight through a planetary atmosphere.
  - For lunar missions it is relevant to Earth return missions
- **Ablative materials**, such as fully dense **Carbon-Phenolic** (C-P) and **PICA**, can tolerate **~1 kW/cm²**.
- Typical TPS configurations:
  - Monolithic & Tiled
  - Ablative & Reusable (e.g., shuttle)
- Typical **TPS mass fraction** values include: MER (12%); MPF (8.2%); Stardust (22%); **Apollo (13.7%)**; Genesis (18%); Pioneer Venus (13%). Galileo (50%)

Apollo capsule

Luna 24 sample return



Galileo heritage aeroshell concept



Stardust Return Capsule

Technology development could reduce TPS mass fraction by ~25% to 50%.

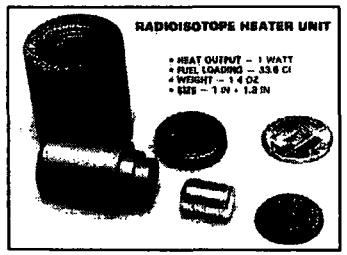
Ref: Venkatapathy, Laub, Wright, "Enabling in-situ science: Engineering of the Thermal Protection System for future Venus Entry Missions," Chapman Conference, Key Largo, Florida, USA, February.13-16, 2006

Protection Systems:

Temperature Mitigation for Lunar In-Situ Missions

- ***Night time & in shadowed craters:***
  - **Isolation** inside WEB
    - **Aerogel**
      (good insulation, no conduction)
      - very low thermal conductivity, ~0.1 W/mK; density ~20 kg/m^3
    - **Multi-Layer Insulation – MLI**
      (great performance in vacuum)
      - made of closely spaced, and layered Mylar or Kapton, coated with thin film of aluminum, silver or gold
    - **Internal heaters**
      - E.g., resistance heating, RHU

- ***Daytime with solar availability:***
  - **Removal of self generated heat** from inside the WEB by
    - reduced internal heating & heat loss through walls
    - by active cooling
      - e.g., fluid loop, heat pipe



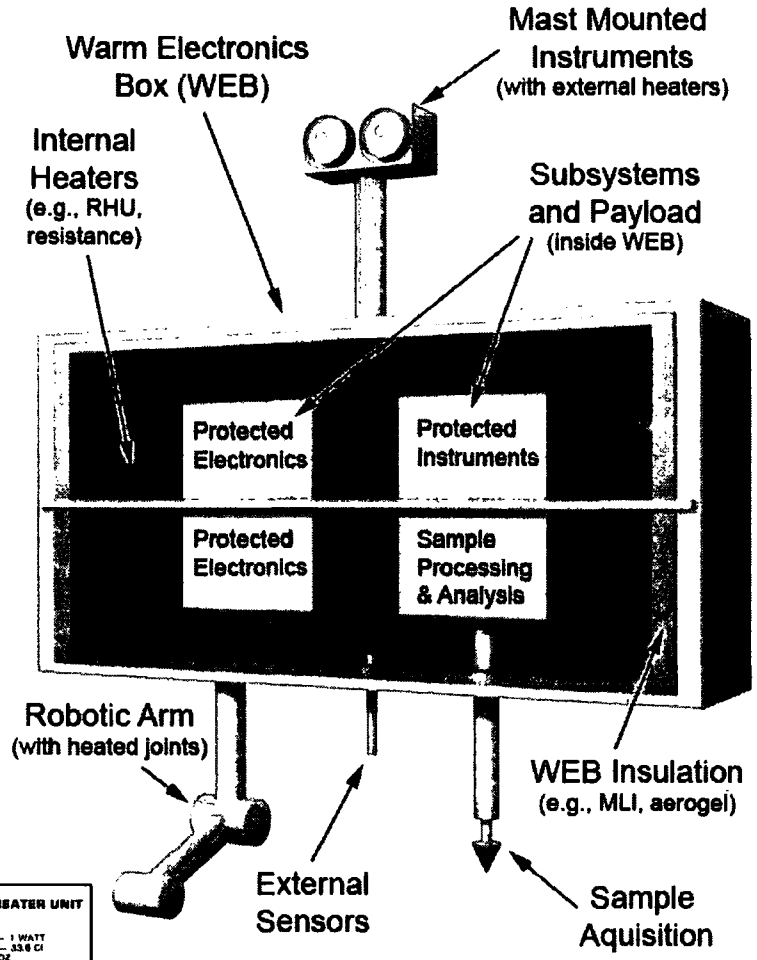


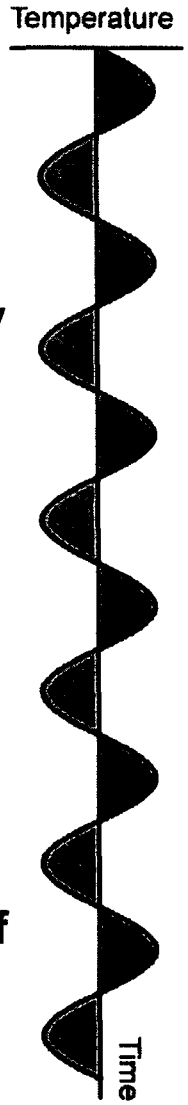
Illustration of low temperature mitigation

Thermal Cycling

- Thermal cycling impacts
  - In situ missions **close to the Sun** (e.g., out to Mars or 1.5 AU), and
  - With **short diurnal cycle** (e.g., Moon, & Mars).

- **Shorter diurnal** cycles **impact thermal cycling** more significantly
  - **Lunar & Mars** in situ missions are **most affected**;
    - Moon: 28 Earth days cycle, with +197°C to -233°C
    - Mars 24.6 Earth hours cycle, with +27°C to -143°C
  - Impact of thermal cycling is also influenced by **landing location**, due to the tilt of the planet or moon.

- For **Lunar missions, low temperatures** are the principle concern
  - Generally, lunar surface missions could be designed with **insulation and active heating** systems to **protect electronics** from the cold environment.
  - However, operational systems designed to tolerate a **high number of cycles** would have the **strongest effect on these missions** (e.g., complexity, cost, risk).



Low Temperature Electronics

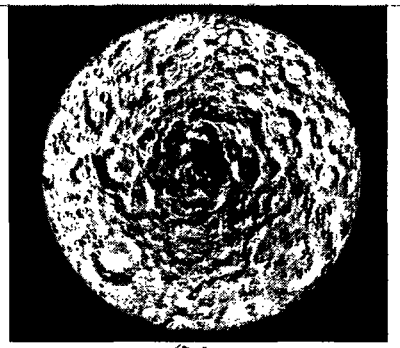
- **Lowest temperatures** at NASA Roadmap mission targets:
  - At the Lunar **South Pole – Aitken Basin** region
  - In **permanently shadowed craters**

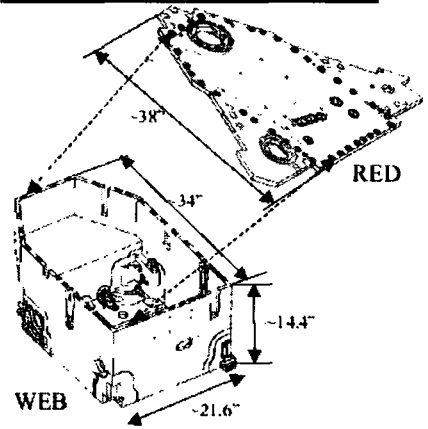
- **Widest temperature swing**:
  - For **rovers** and **hoppers**, which are
  - **Moving** from non-shadowed **to permanently shadowed** regions

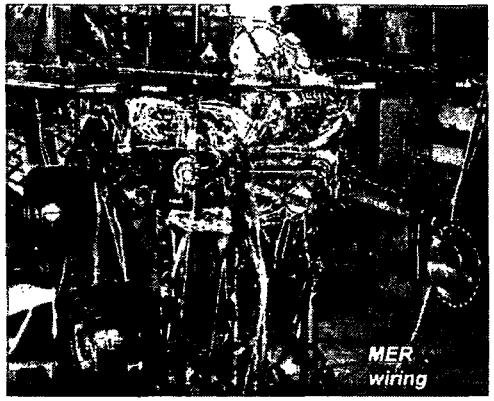
- **State–of–the–Art** (SoA) on low temperature electronics
  - Most commercial off the shelf (**COTS**) and military **electronic circuits** are rated to operate between **−55°C to +125°C**.
  - This necessitates thermal control systems such as a centralized **Warm Electronics Box (WEB)** to protect their electronic subsystems from the temperature extremes.

  - **Limitations** of the WEB approach:
    - Uses **power** relatively **inefficiently**.
    - Complicates the design due to **large wire harness needs** to connect the protected electronics to the various unshielded loads at the extremities of the robotic system (E.g., MER required about 1,800 individual wires).
    - This approach is clearly **not robust**; **not modular**; **not scalable** to significantly more complex robotic exploration systems.

- Anticipated **technology development**
  - **Electronics** that operate **in low temperature ranges**, eliminating the need for a WEB (e.g., Si and SiGe transistors)
    - **Simpler** integrated system; **easier to maintain**
    - Allows for **integrated, modular** subsystems; loosely coupled in **distributed networks**.

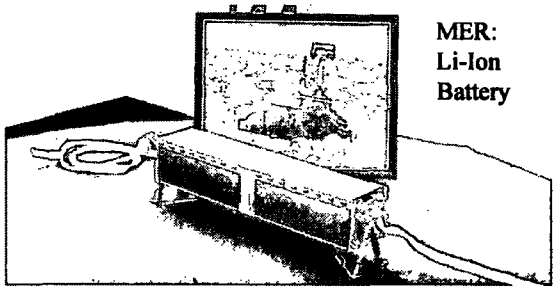






Low Temperature Energy Storage

- Potential **low–temperature energy storage** systems include:
  - i) **Primary** Low–Temperature **Batteries**;
  - ii) **Secondary** Low–Temperature **Batteries** (rechargeable); and
  - iii) **Alternative** Low–Temperature **Energy Storage** Systems
    Flywheels, Superconducting Magnetic Energy Storage, Combustion–Driven Turbine Systems, and Hybrid Systems using thermal batteries.

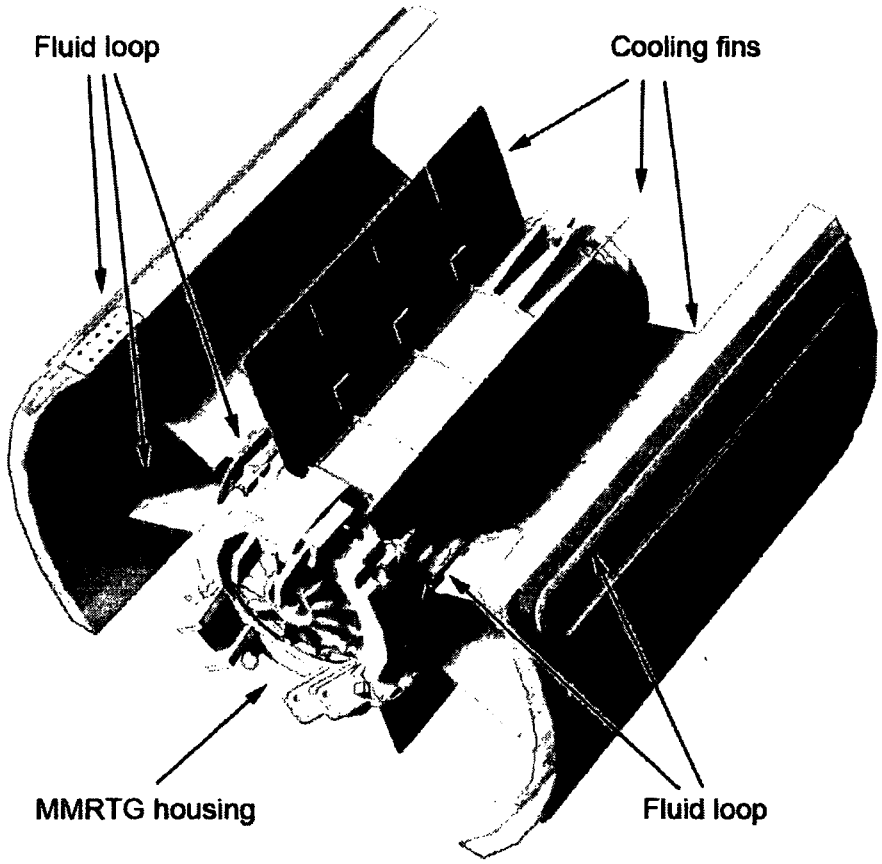


MER: Li-Ion Battery

- **State–of–the-Art** (SoA) on space qualified batteries:
  - Designed to operate at **−20°C to 40°C** range;
  - Virtually all of them **cease to function** at temperatures **below −50°C;**
  - Require **thermal management** system **at lower temperatures**
    - E.g, solar–powered electrical heaters or radioisotope heaters (RHU);
  - Typical primary and secondary battery systems are
    - Ni–Cd, Pb–Acid, Ni–MH, and Zn Carbon, Mg–MnO2, Zn–MnO2; and Li-based;
  - Secondary batteries are typically used in **hybrid power system** configurations
    - E.g, Solar panels + batteries & RPSs + batteries.

- Anticipated **technology development**
  - A number of existing terrestrial primary and rechargeable batteries could **operate at −100°C after some modifications/advancements;**
  - **Advanced Low Temperature Battery**: Limited work on batteries operating at very low temperatures (down to −200°C);
  - **Alternative energy storage devices**: Could be developed to operate at ultra–low temperatures (below −180°C).

Power Generation - MMRTG

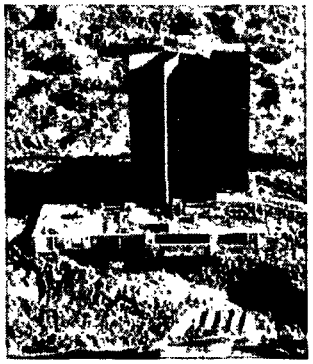


Concept designed for MSL

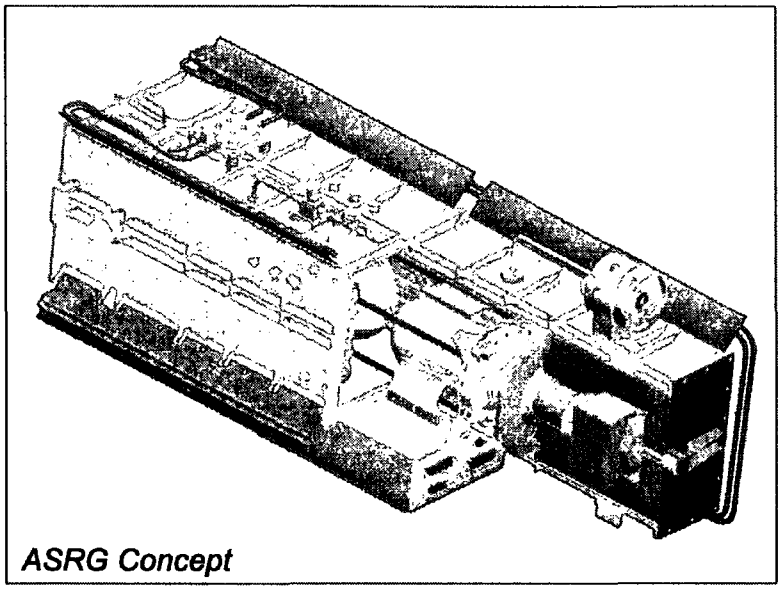
- **Multi-Mission RTG (MMRTG)**
  - **Heat Source:** 8 GPHS modules
  - **Design Life:** 14 Years + Storage
  - **Power BOM/14 years:** 123 We / 97 We
  - **System efficiency:** 6.3%
  - **Mass:** 43.5 kg (2.8 We/kg BOM)
  - **Size:** 66 cm L x 64 cm Diameter fin tip-to-tip
  - **Advantages:** Flight Heritage; Inherent Reliability; Radiation Tolerant; Multi Mission capability; TRL 9 by 2009

Excess heat from the MMRTG could be used for thermal management on Lunar missions

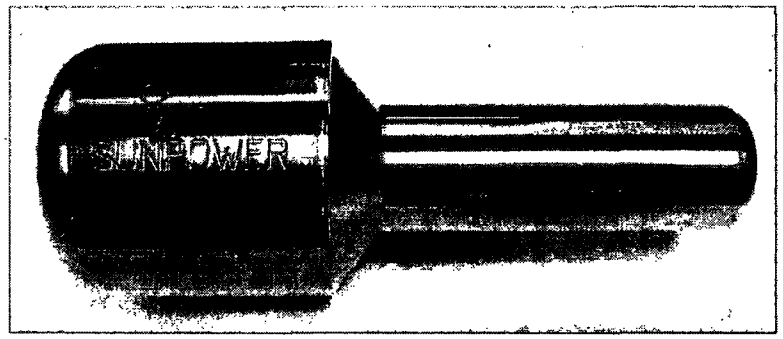
RPSs has been used on the Moon, e.g., on Apollo 16 - ALSEP



Power Generation – ASRG



ASRG Concept



SunPower Stirling Convertor

- **Advanced Stirling Radioisotope Generator (ASRG) – Conceptual**
  - **Heat Source:** 2 GPHS modules
  - **Design Life:** 14 Years + Storage
  - **Power BOM/14 years:** 143 We/126 We
  - **System efficiency:** ~28%
  - **Mass:** ~20.2 kg (7 We/kg BOM)
  - **Size:** 76 cm L x 39 cm W x 46 cm H
  - **Advantages:** High efficiency; High Specific Power; Multi Mission capability; TRL 5/6 by 2008

ASRGs generate ¼ of the excess heat of an MMRTG, however, they also use only ¼ of the fuel, which could provide benefits on larger Lunar missions, requiring more power

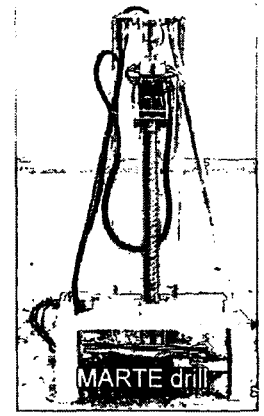
Low Temperature Mechanisms

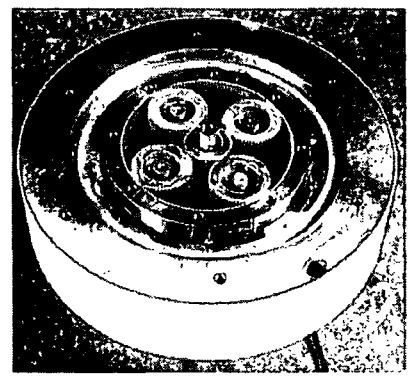
- **Motors & actuators**
  - **Direct interface with the environment**: sample acquisition; mobility, robotic arms, and other applications;
  - **Reliable operation** on the Moon (−233°C to +197°C);
  - Over an **extended periods of time**,
  - **Without or with** very limited **thermal control**;

- **State–of–the–Art** (SoA) on low-T mechanisms
  - **MER; Mars Pathfinder; Apollo rover** → SoA in low-T robotics
  - Operation on Mars → from −115°C to 0°C;
  - Operation of mechanisms, position sensors, gears, bearings, and lubricants **limited to −130°C** and to **1,000,000 revolutions**;
  - Harmonic gears are limited to operation at −80°C.

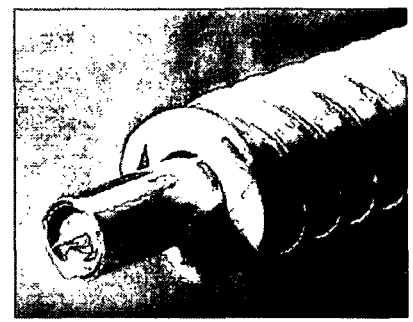
- Anticipated **technology development**
  - Operating temperature: → **down to −233°C**
  - Extended life: → **50,000,000 revolutions** for gears, bearings, and lubricants.
  - Develop: → materials, sensors, actuators, motors, thermal control; electronics; cabling
  - Mechanisms: → to operate in vacuum.

Honeybee: Sample processing





Honeybee: robotic joints



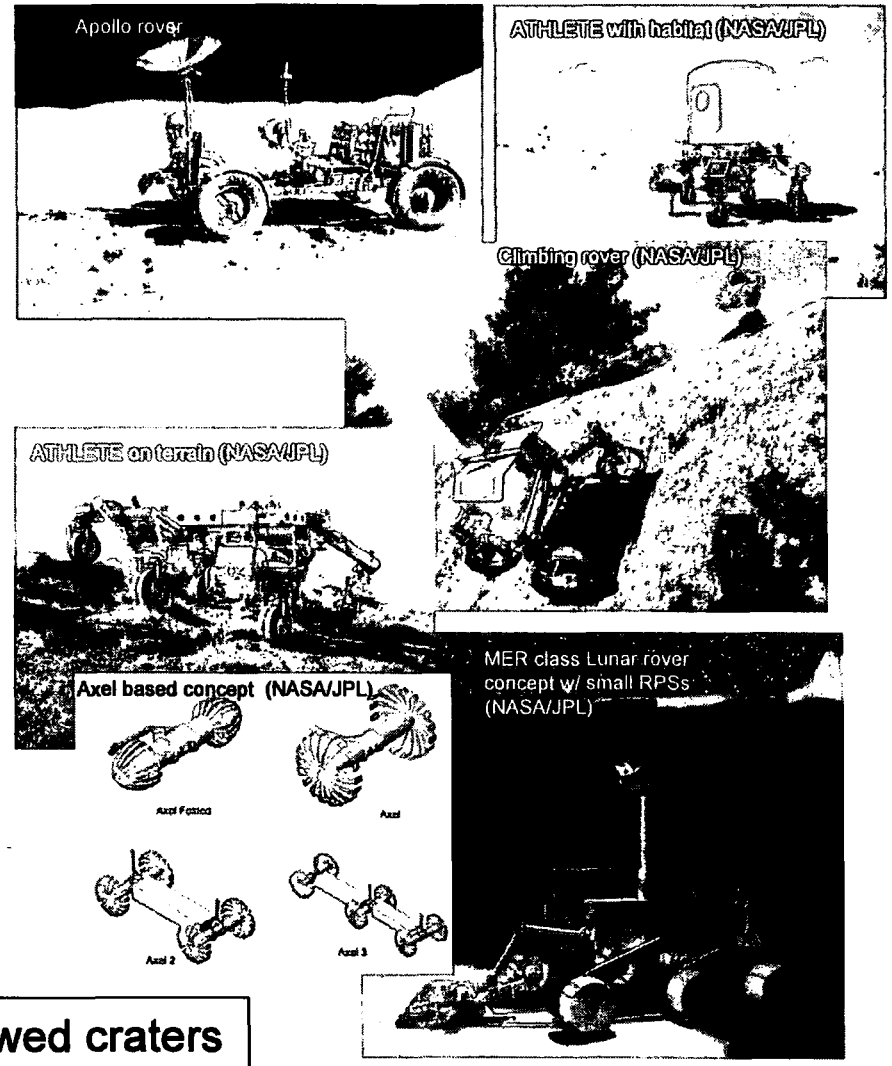
Honeybee: Mini-corer

Apollo rover

Low-T is relatively simple to mitigate, using resistance heating, or possibly Radioisotope Heater Units (RHUs) through contact heating

Surface Mobility

- **Mobility** is one of the **highest power drivers** on a space mission
- In **permanently shadowed craters internal power sources** would be required, such as RPSs
- Small **MER class rovers** would require **~80-120 We for traversing** (equivalent to ~1 RPS)
- Typically rovers would utilize a **hybrid power system**:
  - High power modes: RPS+batteries
  - Low power modes: recharging batteries

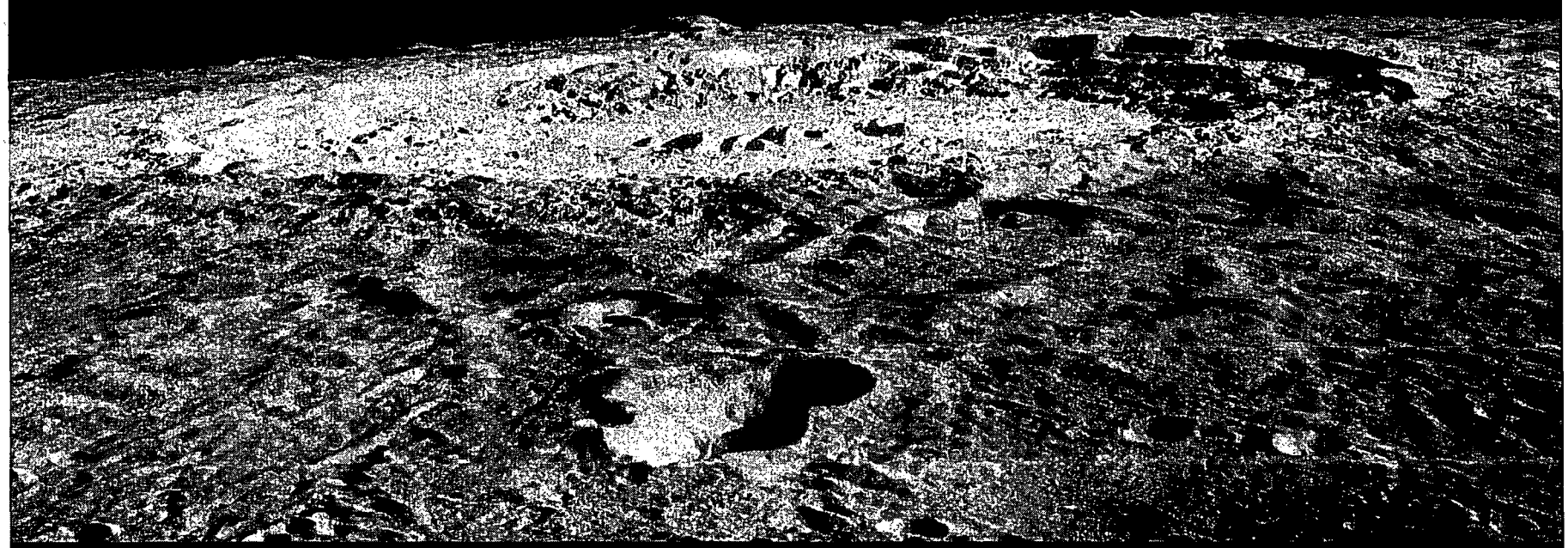


For mobility inside permanently shadowed craters moving parts, motors, actuators need to be heated

Conclusions

- Potential future Lunar missions will likely **encounter multiple extreme environmental conditions**
  - Mitigating these conditions may **require** the development of **technologies, designed for multiple environmental extremes.**
- In general, there may be several **architectural approaches** for coping with these environments,
  - some involving environmental **protection;**
  - others environmental **tolerance;**
  - or a combination of both (i.e., a **hybrid system**).
- Systems analyses and architectural trades will be needed
  - to **develop specific performance targets** for the different technologies;
  - and to establish **priorities in the technology investment** program.
- In summary, **future Lunar missions** are expected to **benefit from technology developments** in
  - Component hardening; low temperature technologies in energy storage; electronics; and mechanisms; while tolerating temperature cycling between extremes.
  - Thermal management, in combination with waste heat utilization from RPSs may play an important role in the exploration of permanently shadowed craters

Thanks for your attention



Ref: Copernicus Crater http://photojournal.jpl.nasa.gov