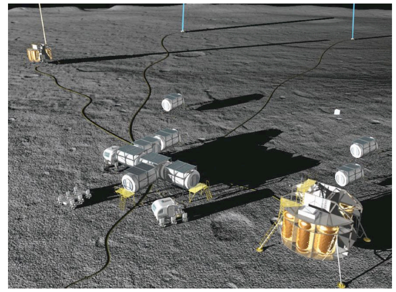
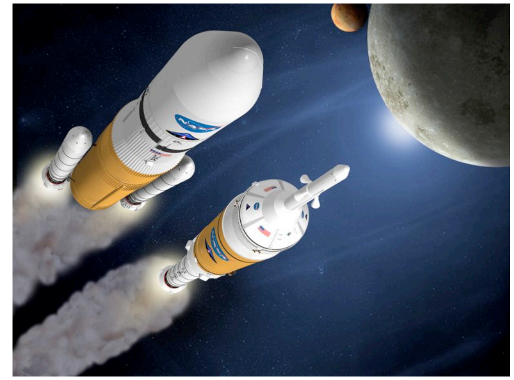
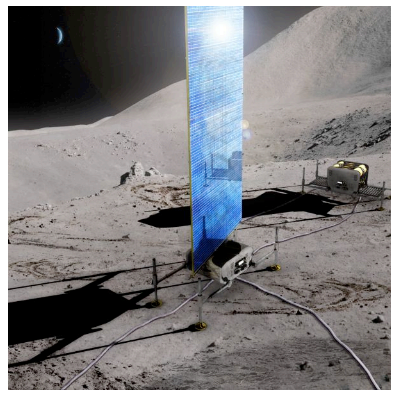
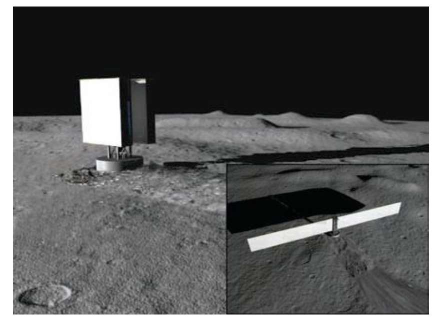
Energy Storage & Power Systems
Technology Needs & Gaps





ESMD Technology Exchange Conference





Galveston Island Convention Center
November 14 & 15, 2007

Dave Hoffman, ARES V Power
Nang Pham, ARES V Power
Rob Button, Lunar Lander Power Lead

Joseph J. Nainiger (NASA Glenn)
Lunar Surface Power Element Lead
Constellation Lunar Surface Systems Office

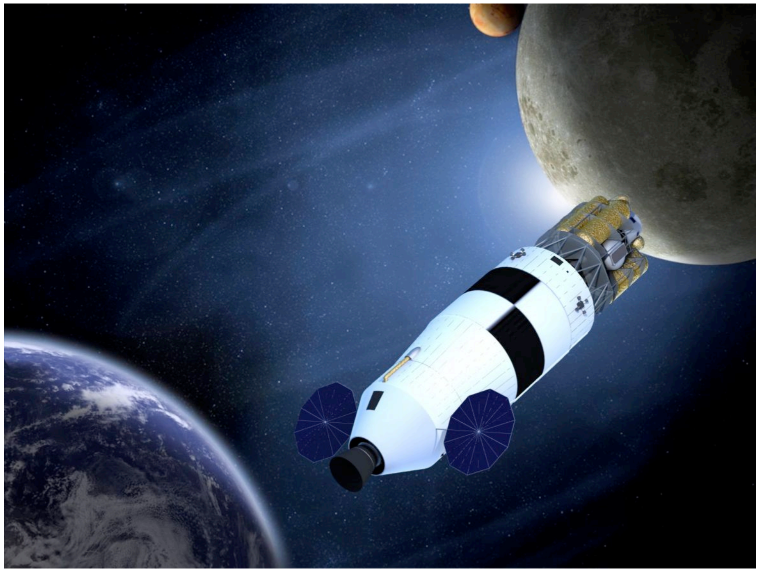
Agenda

- ARES V
- Lunar Lander
- Surface Power (Lunar and Mars)

ARES V Power

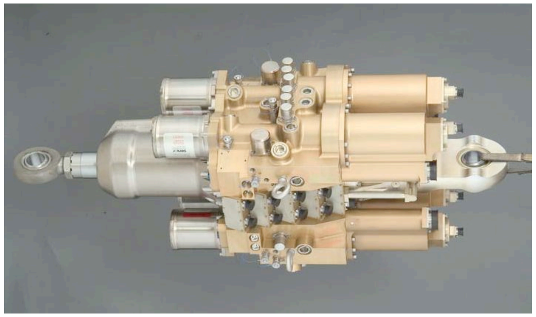
Power for ARES V

- Power for solid rocket booster (SRB) thrust vector control (potential use of electro-hydrostatic actuators)
- Power for core stage systems
- Power for the Earth Departure Stage (EDS) systems (including potentially long Earth orbit loiters)
- Also EDS will supply TBD amount of power to Lunar Lander from launch through trans-lunar injection (TLI) burn



Power for SRB Thrust Vector Control

- Potential use of electrically-powered thrust vector control system has significant weight, operability, safety, and maintainability advantages
- Key component to power source is to have high specific power in order to attain desired weight reduction.
  - High voltage (e.g., 270VDC)
- This power source does not exist.
- Development of high power supply such as high power lithium-based battery or non-toxic turbine-electric power unit is necessary for this system to be viable

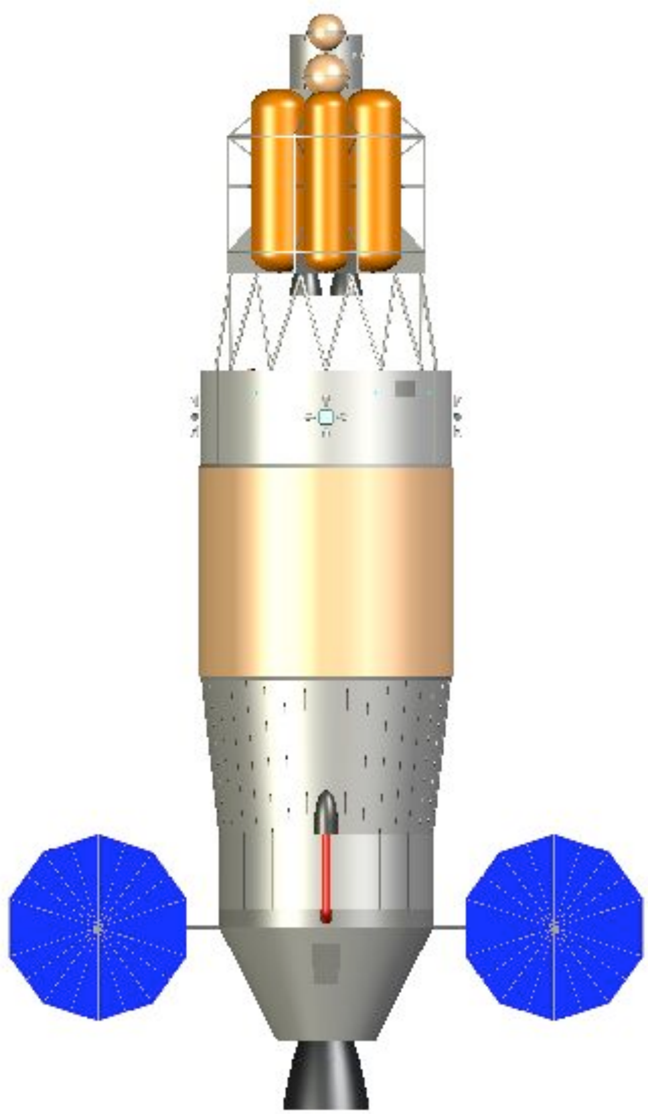


Electro-Hydrostatic Actuator

Non-toxic Turbine-electric Power Unit

EDS Power Architecture Options

- **Solar Array & Lithium-Ion Battery**
  - ↑ Provides for indefinite loiter times
  - ↑ Lower heat rejection requirements
  - ↑ Opportunity for commonality with Orion systems
  - ↓ Performance may be impacted by vehicle attitude during loiter
  - ↓ Requires deployment mechanisms & tracking gimbals
  - ↓ Size array for TLI loads or jettison prior to TLI
- **Primary Fuel Cell**
  - ↑ Opportunity for commonality with Lander systems
  - ↑ Performance not impacted by vehicle attitude during loiter
  - ↑ No significant mechanisms required
  - ↑ TLI loads should not be an issue
  - ↓ Loiter times constrained by reactant budget
  - ↓ Higher heat rejection requirements



Lunar Lander Power

Lunar Design Analysis Cycle (LDAC) Summary

- Initial Lander DAC began 5/1/07, ended 6/30/07.
- Took a “minimal functionality” approach
  - Not intended to be a “flyable” vehicle
  - Provides a starting point for informed risk reduction
  - Provides key data point: if minimally functional vehicle doesn’t fit in the architecture, the architecture is broken
- Primary LDAC1 design figure of merit: maximize payload to the surface of the Moon with a crewed Lander
- LAT strategy was to build up a lunar outpost by incremental deliveries with a crewed Lander
  - Goal of 6 metric tons delivery capability; strategy unworkable if delivery capability is less than 4 metric tons
- LDAC1 minimum functional Lander delivered less than the 4 metric tons of payload required with crewed Lander
- Conclusion: Cargo variant of Lander is required to build up the lunar outpost
- LDAC1 “delta”
  - Re-designed the Lander to focus on the Cargo lander capability.
  - Investigate new vehicle configurations in order to drive down structure and module mass.
  - LDAC1-delta completed October 31, 2007.

LDAC-1 Starting Point (cont.)

- 3 DRMs with Mission Timelines and Functional Allocations
  - Sortie Mission to South Pole
    - 4 Crew / 7 Days on Surface / No support from surface assets
    - No restrictions on 'when' (accommodating eclipse periods)
  - Outpost Mission to South Pole
    - 4 Crew with Cargo Element (LAT2 Campaign option 2)
    - Outpost provides habitation on surface (down and out)
    - 210 Days with surface support (power)
  - Cargo Mission to South Pole
    - Short duration, large payload
- One Lander design, with variants (kits) if required for the different DRMs

LDAC1 Lander Sortie Configuration

LDAC1 Power Subsystem Operational Concepts

- Operational Concepts for a minimally functional vehicle
  - Lander is launched un-powered.
  - Shortly after achieving LEO, the Lander is powered-up and “checked out” for 3 hours.
  - Following check-out, the Earth Departure Stage (EDS) provides 1.5kW to Lander for quiescent power requirements during a 14-day loiter.
  - The CEV (Orion) docks to Lander in LEO. Prior to the Trans-Lunar Insertion (TLI) burn, the EDS cuts off power and Lander gets 600W from CEV while in LEO.
    - Lander may have to augment or provide own internal power during this period.
  - Following TLI, CEV provides 1.5kW to Lander
  - Lander powers-up 24 hrs prior to the Lunar Orbit Insertion (LOI) burn. Provides full power to itself through the rest of the mission.
    - About 50 hrs. during in-flight and landing phases.
    - About 168 hrs. during a 7-day Sortie mission on the lunar surface.
  - The Outpost and Cargo Lander plug-in to a surface power system to maintain the Lander during a 210-day waiting period prior to ascent.
  - The Lander is self-powered during ascent to CEV and through short docking period.
  - It then un-docks and is disposed of in lunar orbit or a de-orbit burn into the lunar surface.

Technology Needs

- Fuel cell technology needs
  - High power density and high efficiency fuel cell stack.
  - Long life (5000 hours), maintenance-free operation.
    - To be common with surface power
  - Passive "balance of plant" components to decrease power use
  - Increase the reliability and fault tolerance of fuel cells system without adding redundancy.
  - Passive dissolved gas removal from water
  - Ability to separate/filter GHe from mixtures of GH_2/GHe and GO_2/GHe.
- Battery technology needs
  - High energy density secondary battery (200Whr/kg battery)
    - Limited cycles (10 max.)
    - Short shelf/operational life (2 years)
    - Discharge capability between 1-4C
  - Low mass, high reliability circuitry to isolate failed cell(s) or strings.
  - Space qualified fuse for low voltage (24-36Vdc) and high currents (100A cont., 200A peak)
- Power Distribution needs
  - Modular, low-mass remote power controller (28Vdc, 1-2A)
  - Reliable, low-loss primary switchgear (28Vdc, 100-200A)

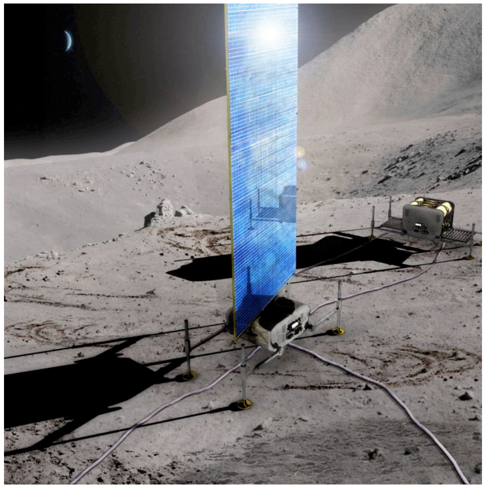
Surface Power

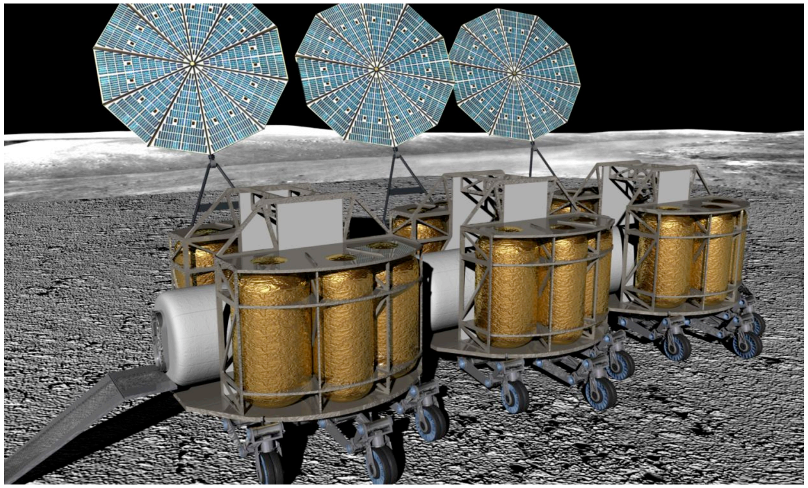
Lunar Architecture Team (LAT) Summary

- **LAT II began 1/22/07, ended 8/31/07**
- **Architectural options evaluated (all at Shackleton Crater rim site)**
  - **Option 1: All elements delivered with crewed flights (LAT 1)**
  - **Option 2: Derivative of LAT 1 except uncrewed lander can deliver hardware to surface provided all elements must be sized to fit on a crewed lander.**
  - **Option 3: A single large, fully outfitted and pre-integrated habitation launched and landed on a single uncrewed mission**
  - **Option 4: The lander has integrated surface mobility (mobile lander)**
  - **Option 5: Long range, pressurized rover delivered as early in the sequence as possible (Captured in each)**
  - **Option 6: Nuclear power used for the surface power in lieu of solar**
- **Power systems**
  - **For options 2 and 3 – multiple stand alone solar array units with multiple stand-alone regenerative fuel cell (RFC) energy storage units**
  - **For option 4 – integrated solar arrays and RFC units with mobile surface landers**
  - **For option 6 – a single fission surface power system emplaced below lunar surface to take advantage of regolith radiation shielding**
  - **For options 2, 3, and 6 – extensive power management and distribution (PMAD) network (including power cabling)**
  - **For option 4 – integrated PMAD with mobile landers**

LAT II Photovoltaic - Regenerative Fuel Cell Systems

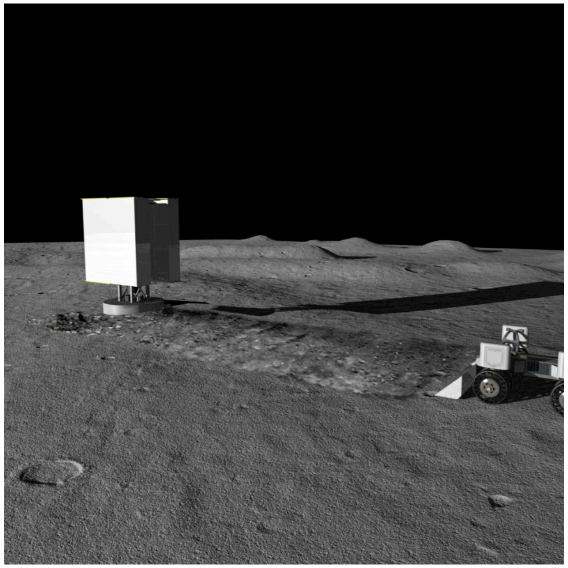
- **Two PV power system design concepts**
  - Stationary solar array included in options 2 and 3
    - Concept derived from rectangular ATK Aurora design
    - Vertical orientation mitigates dust interaction and potential synergy with communications tower
  - Circular array based on ATK Ultraflex design included in option 4
    - May be better for mobile applications
    - Has greater structural integrity
    - Some commonality with Orion arrays
  - Both array types deployed with some potential for limited retract and deploy cycles
  - Both assume 32-percent (BOL) multi-junction cells
- **Options 2, 3, and 4 assume regenerative fuel cells for energy storage**
  - Batteries would be prohibitively massive to meet the energy storage demands

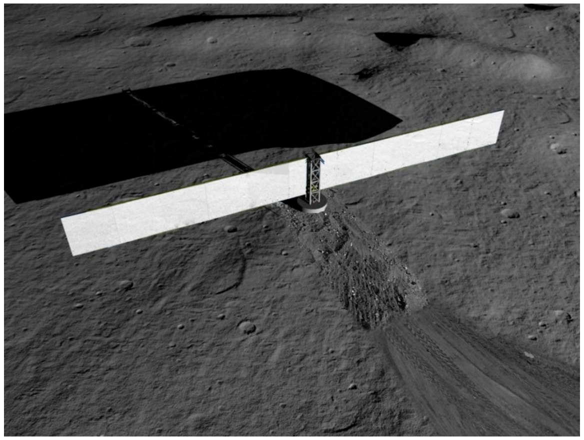




LAT II Fission Surface Power System (FSPS)

- Primary outpost power generation for option 6
- Study trades included
  - Reactor design
  - Power conversion methodology
  - Shielding approaches
- FSPS System characteristics
  - Low temperature, NaK cooled, UO2 reactor
  - Use of regolith for shielding
  - Stirling power conversion
  - Water heat pipe radiators





Surface Power Users

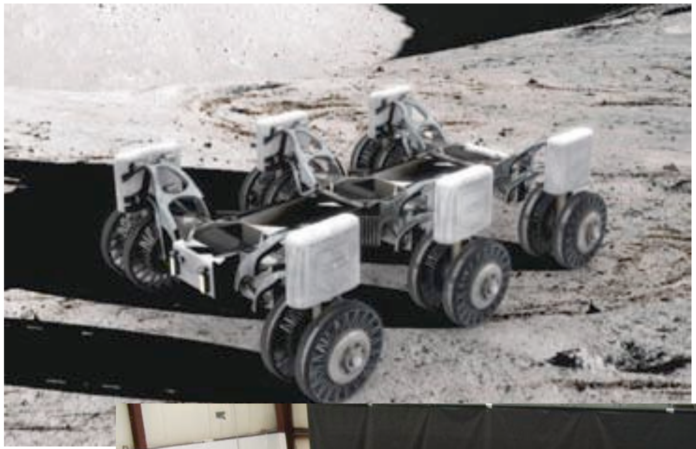
- Primary surface power sources must provide power for
  - Habitats
  - Recharge of rovers
    - Crewed (unpressurized and pressurized)
    - Un-crewed
  - ISRU
  - Keep-alive/standby (Including lander ascent stage and payloads)
  - All of the above for:
    - Each stage of surface outpost build-up
    - When in sun and eclipse/shadow (i.e., must rely on energy storage for solar based power systems)

Lunar Surface Power Requirements

- Location
  - At Shackleton Rim lunar outpost
    - Solar insolation times vary from nearly 100% during summer lunation to 70% during worst case winter lunation
      - Longest eclipse period is ~ 122 hours occurring once/year
  - At locations > 4 degrees latitude from the poles
    - Insolation/lunation is ~ 50%
    - Surface is in eclipse 14.75 days (354 hours) or more
- For solar based power systems at either location, energy storage will pose a significant challenge
  - High energy density, long-lived regenerative fuel cells will be required
- Lunar environments need to be accommodated or mitigated
  - Surface dust
  - Thermal extremes
  - Radiation exposure

Surface Mobility Power Requirements

- Desired mobility capabilities include:
  - Un-pressurized traverses
  - Longer range pressurized mobile explorations
  - Potentially transporting large habitats and other lunar surface assets over long distances
- Power challenges for mobility systems include:
  - Long-lived and reliable energy storage systems
  - With increasing mobility range, power requirements must be met over changing solar insolation, thermal, and terrain features

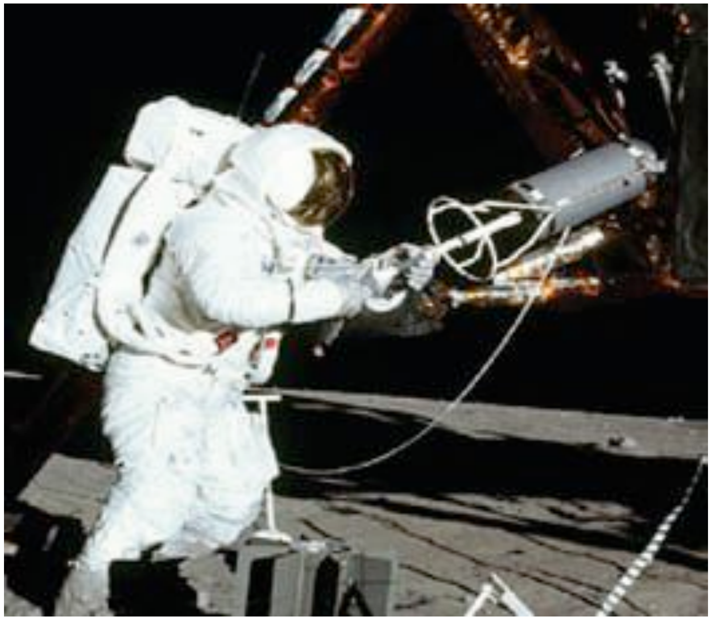


Power Management and Distribution Challenges

- Potential need to transmit power 100s of meters to potentially 1000s of meters
- Need to transmit power safely and efficiently at high voltages
- Need
  - Highly efficient converters/inverters and switchgear
  - High voltage, lightweight, reliable, and efficient cables

Nuclear Power

- Either fission or radioisotope power systems might be considered for surface applications
- Fission surface power
  - Could be considered for stationary surface outpost
  - Use of lunar regolith for radiation shielding is highly desirable to minimize system mass
- Radioisotope power systems
  - Stand-alone science packages (ala RTG powered Apollo Lunar Science Experiments)
  - Keep-alive power source for lunar lander ascent stages/payloads
  - Power for mobility systems (unpressurized or pressurized)



Summary

- Power and energy systems will required for human exploration of the moon and Mars
  - Human life support
  - Communications and navigation
  - Human and robotic mobility systems
  - Planetary surface in-situ resource utilization (ISRU)
  - Vehicle/surface ancillaries
  - Scientific activities
- These systems
  - Need to be highly reliable
  - Have the ability to operate in unique deep space or planetary surface environments
  - Need to be long-lived
  - Need to be "affordable"
- Existing and future technology efforts are charged with meeting these requirements