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Electric Power System Technology Options for Lunar Surface Missions

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Electric Power System Technology Options for Lunar Surface Missions

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Abstract

In 2004, the President announced a "Vision for Space Exploration" that is bold and forward-thinking, yet practical and responsible. The vision explored answers to longstanding question of importance to science and society and will develop revolutionary technologies and capabilities for the future, while maintaining good stewardship of taxpayer dollars. One crucial technology area enabling all space exploration is electric power systems. In this paper, the author evaluates surface power technology options in order to identify leading candidate technologies that will accomplish lunar design reference mission three (LDRM-3). LDRM-3 mission consists of multiple, 90-day missions to the lunar South Pole with 4-person crews starting in the year 2020. Top-level power requirements included a nominal 50 kW continuous habitat power over a 5-year lifetime with back-up or redundant emergency power provisions and a nominal 2-kW, 2-person unpressurized rover.

To help direct NASA's technology investment strategy, this lunar surface power technology evaluation assessed many figures of merit including: current technology readiness levels (TRLs), potential to advance to TRL 6 by 2014, effectiveness of the technology to meet the mission requirements in the specified time, mass, stowed volume, deployed area, complexity, required special ground facilities, safety, reliability/redundancy, strength of industrial base, applicability to other LDRM-3 elements, extensibility to Mars missions, costs, and risks.

For the 50-kW habitat module, dozens of nuclear, radioisotope and solar power technologies were down-selected to a nuclear fission heat source with Brayton, Stirling or thermoelectric power conversion options. Preferred energy storage technologies included lithium-ion battery and Proton Exchange Membrane (PEM) Regenerative Fuel Cells (RFC). Several AC and DC power management and distribution architectures and component technologies were defined consistent with the preferred habitat power generation technology option and the overall lunar surface mission. For rover power, more than 20 technology options were down-selected to radioisotope Stirling, liquid lithium-ion battery, PEM, RFC, or primary fuel cell options. The author discusses various conclusions that can be drawn from the findings of this surface power technologies evaluation.

Presentation Outline

- Introduction
- Study Approach, Guidelines & Assumptions
- Candidate Power Technologies
  - Habitat/ISRU
  - Human Unpressurized Rover
- Technology Assessment Results
- Recommendations & Findings

April 21, 2005 2005 Space Power Workshop Chart 1

Introduction

- **6-week, Internal NASA study (Spring 2004)**

- **Study power team members**
  - JSC/Tim Lawrence, GRC/Ray Beach

- **Purpose**
  - Derive complete set of lunar surface system technology options
  - Enable DRM-3 mission scenario
    - 30-90 day stay at lunar polar site
  - Identify potential to advance to TRL 6 by 2014
  - Identify programmatic cost and risk metrics

April 21, 2005 2005 Space Power Workshop Chart 2

Approach

- Fill-in needed requirements/assumptions
- Create figures of merit (FOMs)

- Identify broad range of candidate power technologies
  - Data from literature review & subject matter experts
  - Calculations & scaling
  - SOA & Advanced
- Prescreen candidate technologies
  - Eliminate poor performers & immature technologies

- Compare remaining technologies using FOMs
  - Capture data & references in Excel spreadsheet
- Recommend leading technologies

April 21, 2005 2005 Space Power Workshop Chart 3

Key Guidelines/Assumptions

- **30-90 day (*90 day*) mission to lunar south pole in 2020**
  - Exact landing site unspecified
- **3-10 year operating life *(nominal 5-year)***
  - 5 missions to same site, once per year
- **20-100 kW *(nominal 50 kW)* habitat power system**
  - *Shared nuclear heat source, 3/2 redundant dynamic converters & radiators*
  - *240 kW-hrs energy storage*
- ***1-3 kW (nominal 2 kW)* rover power system**
  - *Shared isotope heat source & radiator, dual redundant dynamic converters*
  - *8-hr sortie/8-hr recharge periods*
- **Subsystem TRL 6 by ~2014**

Assumptions in italics

April 21, 2005 | 2005 Space Power Workshop | Chart 4

NASA Technology Readiness Levels (TRLs) [Mankins 2001]

TRL 9 Actual system flight proven through successful mission operations.

TRL 8 Flight System completed and qualified through test and demonstration.

TRL 7 System prototype demonstrated in a space environment.

<u>TRL 6 System Prototype Demo in Relevant Environment</u>

TRL 5 Component and/or breadboard validated in relevant environment.

TRL 4 Component and/or breadboard validated in laboratory environment.

TRL 3 Critical function or characteristic demonstrated (proof-of-concept).

TRL 2 Technology concept and/or application formulated.

TRL 1 Basic principles observed and reported.

April 21, 2005 | 2005 Space Power Workshop | Chart 5

Power Technology *Quantitative* Figures of Merit (FOMs)

- Mass, kg/kW
  - Includes heat source, conversion, heat rejection & PMAD hardware
- Deployed Area, m^2/kW
- Volume, m^3/kW
- Energy Storage Specific Energy, W-hr/kg
  - Includes mass of integration elements

April 21, 2005 2005 Space Power Workshop Chart 6

Qualitative Power Technology FOMs (3 of 16)

FOM	High	Medium	Low
Funding to Achieve TRL 6	> $100's M	$10's M	< $10 M
Extensibility to Future Human Mars Mission Power (Surface, In-Space, NEP, NTR)	Meets 3 or more elements	Meets 2 elements	Meets 1 or less elements
Deployment Complexity (# major deployment steps)	5 or more	4	3 or less

April 21, 2005 2005 Space Power Workshop Chart 7

Power Technology Assessment

50 kW Habitat Power
Technology Results

April 21, 2005 — 2005 Space Power Workshop — Chart 8

Nuclear Fission Reactor

- **Identified space power reactor options:**
  - Liquid metal cooled (SP-100)
  - Gas cooled (Escort)
  - Heat pipe cooled (SAFE)
- **All options are leading technology candidates:**
  - Acceptable mass, volume; technology heritage
- **Liquid metal cooled technology:**
  - Best reactor/shield compactness
  - Lowest mass
- **To avoid multiple shield penetrations in heat pipe cooled**
  - Engine fluid loop and/or heat exchanger on reactor side of shield

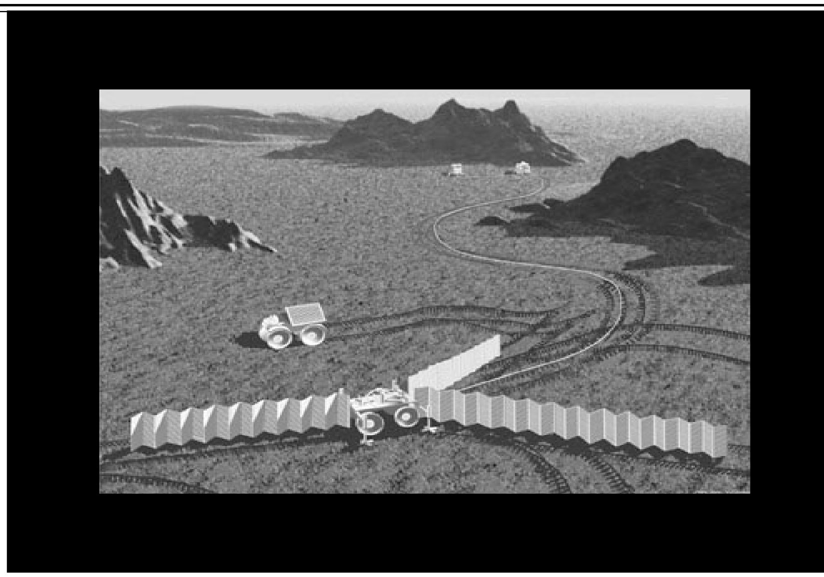
April 21, 2005 — 2005 Space Power Workshop — Chart 9

Nuclear Reactor Shielding

- **Technology Options:**
  - Layered LiH/W or Be/DU (thermal control needed)
  - 4π shielding collocated with habitat
    - Human-rated
    - Instrument-rated plus regolith shielding
  - Remote, “instrument-rated + $\pi/2$ human-rated sector”
- **Collocated reactor shielding options eliminated:**
    - high mass
    - insufficient TRL for regolith handling equipment
- **Leading technology candidate:**
  - Remote, LiH/W, instrument rated + $\pi/2$ human-rated sector shield
  - ~3000 kg shield mass (100 kW system 2.5-km from habitat)

April 21, 2005 2005 Space Power Workshop Chart 10

Power Technology Assessment



April 21, 2005 2005 Space Power Workshop Chart 11

Surface Reactor Power Conversion

- Technologies Eliminated
  - Direct Potassium Rankine (working fluid activation)
  - In-direct Potassium Rankine (insufficient TRL)
  - Organic Rankine Cycle (ORC) (high mass)
  - Combo Thermoelectric (TE)/ORC (high mass, large radiator)
  - AMTEC, MLQW TE (insufficient TRL)
  - In-core Thermionic [TFE-CsO] (insufficient TRL)
  - Themophotovoltaic (TPV) (high mass, large radiator)
  - Combo Brayton/ORC (no mass benefit, large radiator, greater complexity)

April 21, 2005 2005 Space Power Workshop Chart 12

Surface Reactor Power Conversion (Continued)

- Competing technologies key FOMs (SOA technology, 50 kW)

Technology	Mass, kg/kW	Rad. Area, m^2/kW	TRL	Funding To Achieve TRL	Extensibility To Human Mars Mission
Brayton	125	2.7	4	high	high
Stirling	120	1.6	4	high	medium
TE	136	1.4	5	high	medium

April 21, 2005 2005 Space Power Workshop Chart 13

Radioisotope Power Conversion

- **All Habitat radioisotope power technologies eliminated**
  - All GPHS-based technologies ($^{238}PuO_2$ availability)
    - Half US civilian production, stockpile 10 years = > ~2 kW converter
  - ^{241}Am Alphavoltaic, boron-nitride converter (insufficient isotope availability, poor mass scaling above mW level, launch safety)
  - ^{3}H-amorphous silicon (a-Si) Betavoltaic converter (poor mass scaling above mW level)
  - ^{3}H-phosphor, Si or a-Si photovoltaic converter (poor mass scaling above mW level)

April 21, 2005 | 2005 Space Power Workshop | Chart 14

Collocated Solar Photovoltaic & Dynamic Power Conversion

- If collocated with habitat in permanently shadowed basin
- **All solar photovoltaic & solar dynamic technologies eliminated**
  - Lack of sunlight

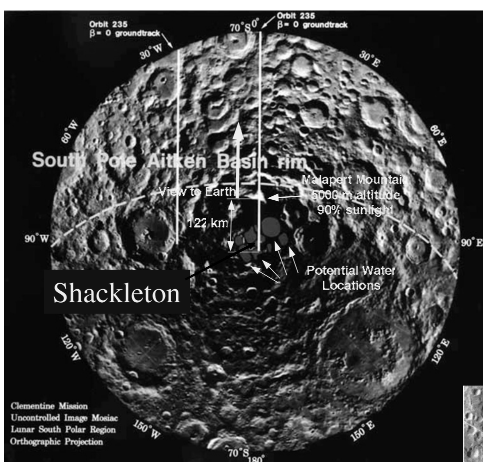
April 21, 2005 | 2005 Space Power Workshop | Chart 15

Solar Photovoltaic Power-Tower Systems

- **All technology options eliminated**
  - All impose mission launch window restrictions
  - 700-m tower deployed from habitat
    - High mass (2X reactor options), Insufficient tower TRL
    - Requires precision landing in known terrain region
  - Power cart deployment to:
    - Shackleton Crater North Rim Massif (35°-40° incline)
      - Incline exceeds rover locomotion limit (30°-35°) on friable slopes
      - Excessive regolith depth near craters
    - Malapert Mountain
      - Low rover TRL
      - Excessive operational risk (60-100 Km deployment)

April 21, 2005 2005 Space Power Workshop Chart 16

Lunar South Pole



Mt. Malapert is located 122 Km from the South Pole at 84.9S, 12.9E: It is a 5-Km high, 69-Km wide.

Yearly insolation: 89% full, 4% partial, 7% none. Shaded periods last 5+ days, 5 times per year.

Mt. Malapert is 60-Km to 100-Km away from areas that may contain water ice (shown in blue on left).

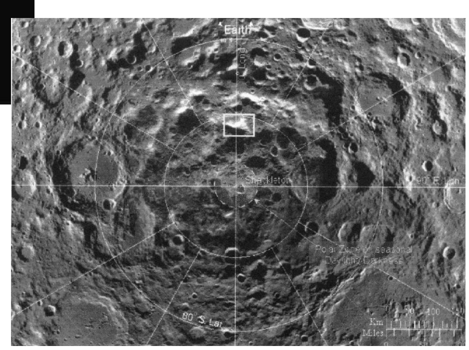
The top is a plateau approximately 10 Km^2 in area.

Mt. Malapert is shown in the yellow box to the right

The South Pole (center) is located on the rim of the Shackelton Crater.

Notice the irregular terrain between Mt. Malapert and the South Pole

Notice the deep depressions between Mt. Malapert and the South Pole



Beamed Power Conversion Systems

- All power beaming technologies eliminated
  - High mass-10X, Insufficient TRL
- RF transmitter/receiver
  - 3 satellites
    - 357-m diameter transmit antenna (50-100 MT antenna mass)
    - 8 MWe power (> 40 MT system mass)
  - 134 m x 134 m auto-deployed, surface rectenna
- Laser diode transmitter/PV receiver
  - 3 satellites
    - ~34-m transmit dish
    - 0.025-μrad pointing system
    - 200 kW transmit satellite (90 MT)

April 21, 2005 2005 Space Power Workshop Chart 18

Habitat Energy Storage

- Technologies eliminated:
  - Polymer Li Ion battery (insufficient TRL)
  - Solid oxide fuel cell (noncompetitive stack power density, insufficient TRL)
  - Flywheel system (high mass)
  - Thermal phase change material (eliminated w/Solar Dynamic option)
- Competing technology key FOMs (SOA)

Technology	Sp. Energy, W-hr/kg	Rad. Area, m^2/kW	TRL	Funding To Achieve TRL	Extensibility To Human Mars Mission
Liquid Li Ion Battery	90	n/a	5	medium	high
PEM-RFC	412	1.0	4	medium	high

April 21, 2005 2005 Space Power Workshop Chart 19

Power Management and Distribution System (PMAD)

- **Eliminated Technologies:**
  - Low Frequency AC Distribution (high mass)

- **Candidate Technologies**
  - 3Φ AC (~ 1000-Hz), High Voltage (~ 1000-V) [Alternator]
  - High Voltage DC [Stirling, TE]
    - Low Mass, High Frequency DC-to-DC Converters
  - Ring & Star Distribution Architectures
    - Ring may have better efficiency, load management capability
  - Electronics Reliability Improved Through Use Of SiC
    - SOA Silicon Capable With Box Level Redundancy

April 21, 2005 2005 Space Power Workshop Chart 20

Heat Rejection

- Insufficient time to complete evaluation of identified technology options
- Heat rejection technology important for all high-power conversion options
- Recommend further study

April 21, 2005 2005 Space Power Workshop Chart 21

Power Technology Assessment

2 kW Human Rover

Power Technology Results

April 21, 2005 2005 Space Power Workshop Chart 22

Human Rover Power Technologies

- **Technologies eliminated**
  - **All nuclear reactor** power conversion options (high mass)
  - **All solar** PV & dynamic conversion options (lack of sunlight)
  - O_2/CH_4 internal combustion engine; Flywheel system (high mass)
  - Solid oxide fuel cell (noncompetitive stack power density, insufficient TRL)
  - Polymer Li Ion battery (insufficient TRL)
  - Radioisotope power conversion technologies
    - **All power technologies eliminated for >2 kWe ($^{238}PuO_2$ availability)**
    - Direct Potassium Rankine (insufficient TRL)
    - AMTEC, MLQW TE (insufficient TRL); SiGe TE (high mass)
    - Combo TE/ORC, ORC (large radiator area)
    - Brayton, TPV (high mass & large radiator area)
    - Out-of-core CsO-triode thermionic (high mass, insufficient TRL)
    - Combined cycle - Brayton/ORC (high mass)

April 21, 2005 2005 Space Power Workshop Chart 23

Human Rover Power Technologies (Continued)

- Competing technology key FOMs **(SOA)**

Technology	Mass, kg/kW	Rad. Area, m^2/kW	Vol., m^3/kW	TRL	Funding To Achieve TRL	Extensibility To Human Mars Mission
Radioisotope/ Stirling	100	2.2	***	4	medium	low
Liquid Li Ion Battery	118	n/a	0.04	5	medium	high
2^{nd} PEM RFC	82	1.0	0.22	4	medium	medium
Primary PEM FC	40	1.0	0.14	4	medium	medium

April 21, 2005 2005 Space Power Workshop Chart 24

Power Technology Assessment

Power Technology Recommendations

April 21, 2005 2005 Space Power Workshop Chart 25

50 kW *Habitat* Power
Leading Technologies & Findings

- **On the basis of FOMs:**
  - **Nuclear fission reactor**
    - LiH/W layer, $\pi/2$ sector shield
    - Deployed via power cart 2.5 Km from habitat
  - **Brayton, Stirling or Thermoelectric Power converter**
  - **NaK pumped loop** coupled to **deployable heat pipe radiator**
- **Technology Findings:**
  - 50 kW System - ~6 MT Mass, ~100-m2 Radiator
  - Favorable Brayton scaling at higher power
  - Favorable Stirling & TE scaling at rover power levels
  - Dynamic & Static Converters rely on "dynamic" liquid metal loops
    - Heat source & heat rejection

April 21, 2005 2005 Space Power Workshop Chart 26

2 kW *Rover* Power
Leading Technologies & Findings

- **On the basis of FOMs:**
  - Independent (contingency), **Radioisotope/Stirling** Converter
    - ~180-kg mass & ~3-m^2 radiator (battery peaking power)
  - Rechargeable (dependent)
    - **Liquid Li-ion Battery**
      - ~200-kg mass, 0.1-m^3 volume & no radiator
    - **PEM RFC System**
      - 160-kg mass, 0.5-m^3 volume and 2-m^2 radiator
- **Findings:**
  - Primary PEM fuel cell has ½ mass (fluid interface complexity)
  - Radiator configurations:
    - Deployed, vertical, top-mounted = minimal dust collection
    - Fixed, horizontal, roof mounted
      - Will tend to collect dust
      - Aids rover equipment & crew thermal control

April 21, 2005 2005 Space Power Workshop Chart 27

References

1. Allen, Daniel T., et al., 2003, “High Efficiency Thermoelectrics in Nuclear Electric Propulsion Reactor Power Systems,” Space Technology and Applications International Forum, Volume 654, no. 1, p. 384-396, Albuquerque, NM, February 2-5.
2. Anderman, Menahem, 1994, “Lithium-polymer Batteries for Electric Vehicles: A Realist View,” Solid State Ionics 69, p. 336-343.
3. Angirasa, Devarakonda, et al., 2003, “Radiator Concepts for Nuclear Powered Brayton Conversion Systems,” Space Technology and Applications International Forum, Volume 654, no. 1, p. 605-612, Albuquerque, NM, February 2-5.
4. Anonymous, 1972, “Apollo 17 Press Release,” # 72-220K, November 26. Anonymous, circa 1987, “Solar Dynamic ORC,” Sundstrand Corp.
5. Anonymous, 2001, “Record of the Decision for the Programmatic Environmental Impact Statement for Accomplishing Expanded Civilian Nuclear Energy Research and Development and Isotope Production Missions in the United States, Including the Role of the Fast Flux Test Facility,” Federal Registry, Vol. 66, No. 18, Notices, US Department of Energy, January 26.
6. Anonymous, 2004A, “General Purpose Heat Source (GPHS) Interface Design Description (IDD): Revision 1,” Orbital Sciences, Feb 16.
7. Anonymous, 2004B, “Draft 250 kWe Growth Study Report,” Oak Ridge National Laboratory, Boeing-Rocketdyne Co., Swales Aerospace Co., NASA Glenn Research Center, April.
8. Anonymous, 2004C, http://education.jlab.org/.
9. Anonymous, 2004D, http://www.automorrow.com/articles/betavoltaic.html.
10. Anonymous, 2004E, http://ares.jsc.nasa.gov/HumanExplore/Exploration/EXLibrary/docs/ApolloCat/Part1/LRV.htm
11. Anonymous, 2004F, http://www.frc.ri.cmu.edu/projects/lri/Luna/design/lunar-facts.html
12. Bennett, Gary L., et al., 1989, “On the Development of Power Sources for the Ulysses and Galileo Missions,”Proceedings of the European Space Conference, p. 117-121, Madrid, Spain, 2-6 October.
13. Bennett, Gary L., 2003, “Power for Space Science Missions: The Nuclear Option,” 41st Aerospace Sciences Meeting & Exhibit, Reno, NV, AIAA paper 2003-1109, 6-9 January.
14. Bents, D.J., et al., 1992, “Design of Small Stirling Dynamic Isotope Power System for Robotic Space Missions,” NASA TM-105919, October.
15. Berkelman, P., et al., 1995, “Design of a Day/Night Lunar Rover,” Technical Report CMU-RI-TR-95-24, Robotics Institute, Carnegie Mellon University, June, Bhardwaj, Manoj, et al., 1992, “Design of a Pressurized Lunar Rover,” NASA CR-192033, April 24.
16. Bland, T.J., et al., 1988, “Status of Organic Rankine Cycle for Space Applications,” 5th Symposium on Space Nuclear Power Systems, p.135-138.
17. Bost, Donald S., 1988, “Trade Study for kWe Class Space Reactors,” New Mexico University, Transactions of the 5th Symposium on Space Nuclear Power Systems, p. 393-396, January 1.
18. Burke, Kenneth A., 1999, “High Energy Regenerative Fuel Cell Systems for Terrestrial Applications,” NASA TM-1999-209429.
19. Burke, Kenneth A., 2003A, “Fuel Cells for Space Science Applications,” NASA TM-2003-212730.
20. Burke, Kenneth A., 2003B, “Unitized Regenerative Fuel Cell System Development,” NASA TM-2003-212739.
21. Bussey, D.B.J., et al., 1999, “Illumination Conditions at the Lunar Poles,” Lunar & Planetary Science 30, abstract #1731, Lunar and Planetary Institute, Houston, TX, March.
22. Cable, Thomas L., et al., 1996, “The TMI Regenerable Solid Oxide Fuel Cell,” Space Electrochemical Research and Technology, p. 109-117, NASA-CP-3337, December.
23. Cataldo, Robert L., 1997, “Power System Considerations for Human Exploration of Mars,” IAF-97-R.1.03, 48th International Astronautical Congress, Turin, Italy, Oct. 6-10, 1997.

24. Cataldo, Robert, and Gill, 2004, "Application of Solar and Nuclear Power for Human Mars Missions," White Paper, May.
25. Crowley, Christopher, et al., 2004, "Thermophotovoltaic Power Conversion Technology for Radioisotope Power Systems," NASA Contract NAS3-03117, Creare Inc., Midterm Review, Hanover, NH, April 14.
26. El-Genk, Mohamed S., 2003, "Energy Conversion Options for Advanced Radioisotope Power System," Space Technology and Applications International Forum, Volume 654, no. 1, p. 368-375, Albuquerque, NM, February 2-5.
27. Hojnicki, Jeffrey S., 2003, "Space Fission Reactor Power System-Rankine Cycle Power Conversion System," NASA Glenn Research Center, White Paper.
28. Houts, Mike, et al., 2003, "Hardware Based Technology Assessment in Support of Near-Term Space Fission Missions," Space Technology and Applications International Forum, Albuquerque, NM February 2-5.
29. Hunt, M.E., 1992, "Dynamic Isotope Power Systems for FLO," NASA Lyndon B. Johnson Space Center, 3rd SEI Technical Interchange: Proceedings, p. 364-372, May 5-6.
30. Jense, 2004, "Solid Oxide Fuel Cell," http://asyncbrain.baf.cz/sanatorium/1/h2fuel/.
31. Joyner, C. Russell, 2000, "The Synergistic Application of Chemical Rocket Component Technologies to the ESCORT Nuclear Bimodal System," 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference 16-19 July, Huntsville, Alabama.
32. Juhasz, Albert J., et al., 2000, "Parametric Study of Radiator Concepts for a Stirling Radioisotope Power System Applicable to Deep Space Missions," NASA TP-2000-209676, June.
33. Kerslake, Thomas W., 2003A, "Effect of Voltage Level on Power System Design for Solar Electric Propulsion Missions," NASA TM-2003-212304.
34. Kerslake, Thomas W., et al., 2003B, "Durability of ITO-MgF2 Films for Space-Inflatable Polymer Structures," paper AIAA-2003-5919, 1st International Energy Conversion Engineering Conference, Portsmouth, VA, August 17-21.
35. Kohout, Lisa, 1999, "Proton Exchange Membrane Regenerative Fuel Cell Sizing Tool", Excel spreadsheet, January.
36. Kohout, Lisa L. and Schmitz, Paul C., 2003, "Fuel Cell Propulsion Systems for an All-Electric Personal Air Vehicle," NASA TM-2003-212354.
37. Kruijff, Michiel, 2000, "The Peaks of Eternal Light on the Lunar South Pole How They Were Found and What They Look Like," 4th International Conference on Exploration and Utilization of the Moon (ICEUM4), ESA/ESTEC, SP-462, September.
38. Lahey, Richard T., and Dhir, Vijay, 2004, "Research in Support of the Use of Rankine Cycle Energy Conversions Systems for Space Power and Propulsion," Scientific Working Group report to NASA.
39. Littman, Franklin D., 1994, "Mars Power System Concept Definition Study, Task Order #16," Vol. 1 & 2, NASA CR 195420, December.
40. Long, Kenwyn J., 1990, "Analysis of Mars Stationary Orbiting Microwave Power transmission System," NASA-TM 101344, July.
41. Lowman, Paul D., 2003, "LSPECS: A Proposed Robotic Astronomy Mission to the Lunar South Polar Regions," International Lunar Conference 2003, August 13.
42. Luke, James R., 2003, "Advanced Thermionic Converter Technology Program", Space Technology and Applications International Forum, Volume 654, no. 1, p. 766-773, Albuquerque, NM, February 2-5.
43. Manzo, Michelle, 2003, "An Overview of the NASA Aerospace Flight Battery Systems Program," 8th Electrochemical Power Systems R&D Symposium, Portsmouth, VA, July 21-24.
44. Mason, Lee S., 1992, "An Evolution Strategy for Lunar Nuclear Surface Power," Arizona University, Proceedings of the Lunar Materials Technology Symposium, February 1.
45. Mason, Lee S., 1999A, "Surface Nuclear Power for Human Mars Missions," NASA TM-1999-208894.
46. Mason, Lee S., 1999B, "Solar Stirling for Deep Space Applications," NASA TM-1999-209656.

47. Mason, Lee S., 2001, “A Comparison of Brayton and Stirling Space Nuclear Power Systems for Power Levels from 1 Kilowatt to 10 Megawatts,” NASA TM-2001-210593.
48. Mason, Lee S., 2002, “Power Technology Options for Nuclear Electric Propulsion,” 37th Intersociety Energy Conversion Engineering Conference, Washington, DC, paper 20159, 28 July-2 August.
49. Mason, Lee S., 2003, “A Power Conversion Concept for the Jupiter Icy Moons Orbiter,” paper AIAA 2003-6007,” 1st International Energy Conversion Engineering Conference, Portsmouth, VA, August 17-21.
50. Miller, Tom, 1999, “Electrochemical Energy Storage: Technology Paths-Batteries,” NASA Glenn Research Center, December 17.
51. Momozaki, Yoichi and El-Genk, Mohamed S., 2003, “Effects of Collector Temperature on the Performance of Grooved Electrode Thermionic Converters,” Space Technology and Applications International Forum, Volume 654, no. 1, p. 757-765, Albuquerque, NM, February 2-5.
52. Murray, Susan, et al., 2004, “Thermophotovoltaic Converter Design for Radioisotope Power Systems,” The Sixth Conference on Thermophotovoltaic Generation of Electricity, Frieburg, Germany, June 14-16.
53. Olszewski, Mitchell, 1987, “Application of Advanced Flywheel Technology for Energy Storage on Space Station,” NASA-Lewis Research Center, Space Electrochemical Research and Technology (SERT), p. 147-156, September 1.
54. Puglia, F., et al., 2002, “Design and Testing of the Mars Exploration Rover Lithium Ion Batteries,” 37th Intersociety Energy Conversion Engineering Conference, Washington, DC, paper 2002-01-3241, 28 July-2 August.
55. Reaves, W.F. and Hoberecht, M.A., 2003, “Proton Exchange Membrane (PEM) Fuel Cell Status and Remaining Challenges for Manned Space Flight Applications,” 1st International Energy Conversion Engineering Conference, AIAA-2003-5963, Portsmouth, VA, August 18-21.
56. Reinhold, Arnold G., 1998, “A Solar Powered Station at a Lunar Pole,” http://world.std.com/~reinhold/lunarpolar.html, March 13.
57. Ryne, Raffealle, 2004, personal communication, “Alphavoltaic & Betavoltaic Converters,” Rochester Institute of Technology, May.
58. Schmitz, Paul C. and Mason, Lee S., 1991, “Space Reactor/Stirling Cycle Systems for High Power Lunar Application,” NASA TM-103698.
59. Schmitz, Paul, 2001, “Flywheel Energy Storage Systems,” Power Computing Solutions, Inc., August.
60. Schrunk, David, et al., 1999, “The Moon: Resources, Future Development and Colonization,” Wiley & Sons.
61. Shanks, Howard R., 2001, “Long Life Power Source,” Iowa Space Grant Consortium.
62. Sharpe, Burton L. and Schrunk, David G., 2002, “Malapert Mountain Revisited,” Space 2002 and Robotics 2002 Conference, Albuquerque, NM, March 17-21.
63. Staniewicz, B., 2003, “From Watts to Megawatts: A Decade of Progress for Saft's Li-Ion Technology,” Saft Inc., December.
64. Thieme, Lanny G. and Schreiber, Jeffrey G., 2000, “NASA GRC Technology Development Project for a Stirling Radioisotope Power System,” NASA TM-2000-210246.
65. Thieme, Lanny G., et al., 2002, “Stirling Technology Development at NASA GRC,” NASA TM-2001-211315/REV1, January.
66. Thieme, Lanny G. and Schreiber, Jeffrey G., 2003, “NASA GRC Stirling Technology Development Overview,” Space Technology and Applications International Forum, Albuquerque, NM, February 2-5.
67. Van Dyke, Melissa, et al., 2001, “The Safe Affordable Fission Engine (SAFE) Test Series,” NASA/JPL/MSFC/UAH 12th Annual Advanced Space Propulsion Workshop, April 3-5.
68. Van Susante, P.J., 2002, “Study Towards Human Aided Construction of Large Lunar Telescopes,” Workshop on Moon Beyond 2002.

69. Williams, M.D., et al., 1993, “Power Transmission by Laser Beam from Lunar-Synchronous Satellite”, NASA TM-4496.
70. Wolff, Frederick, 2001, “Development of a PMAD System for Flywheel Based Energy Storage System,” Space Power Workshop, Redondo Beach, CA, April 3-5.
71. Zagarola, Mark V., et al., 2003, “Developments in Turbo-Brayton Power Converters,” Space Technology and Applications International Forum, p. 580-588, Albuquerque, NM, February 2-5.

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13. ABSTRACT ***(Maximum 200 words)***
In 2004, the President announced a "Vision for Space Exploration" that is bold and forward-thinking, yet practical and responsible. The vision explores answers to longstanding questions of importance to science and society and will develop revolutionary technologies and capabilities for the future, while maintaining good stewardship of taxpayer dollars. One crucial technology area enabling all space exploration is electric power systems. In this paper, the author evaluates surface power technology options in order to identify leading candidate technologies that will accomplish lunar design reference mission three (LDRM-3). LDRM-3 mission consists of multiple, 90-day missions to the lunar South Pole with 4-person crews starting in the year 2020. Top-level power requirements included a nominal 50 kW continuous habitat power over a 5-year lifetime with back-up or redundant emergency power provisions and a nominal 2-kW, 2-person unpressurized rover. To help direct NASA's technology investment strategy, this lunar surface power technology evaluation assessed many figures of merit including: current technology readiness levels (TRLs), potential to advance to TRL 6 by 2014, effectiveness of the technology to meet the mission requirements in the specified time, mass, stowed volume, deployed area, complexity, required special ground facilities, safety, reliability/redundancy, strength of industrial base, applicability to other LDRM-3 elements, extensibility to Mars missions, costs, and risks. For the 50-kW habitat module, dozens of nuclear, radioisotope and solar power technologies were down-selected to a nuclear fission heat source with Brayton, Stirling or thermoelectric power conversion options. Preferred energy storage technologies included lithium-ion battery and Proton Exchange Membrane (PEM) Regenerative Fuel Cells (RFC). Several AC and DC power management and distribution architectures and component technologies were defined consistent with the preferred habitat power generation technology option and the overall lunar surface mission. For rover power, more than 20 technology options were down-selected to radioisotope Stirling, liquid lithium-ion battery, PEM RFC, or primary fuel cell options. The author discusses various conclusions that can be drawn from the findings of this surface power technologies evaluation.

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Electric power; Lunar surface; Solar arrays; Energy storage; Nuclear reactors; Radioisotope heat sources; Fuel cells; Electric generators; Thermal electric power generation; Stirling engines

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