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Electric Power System Technology Options for Lunar Surface Missions

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April 2005

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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.

Lunar Surface Power System Technology Assessment

Space Power Workshop
April 18-21, 2005
Thomas W. Kerslake
NASA Glenn Research Center

Presentation Outline

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

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

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

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

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.

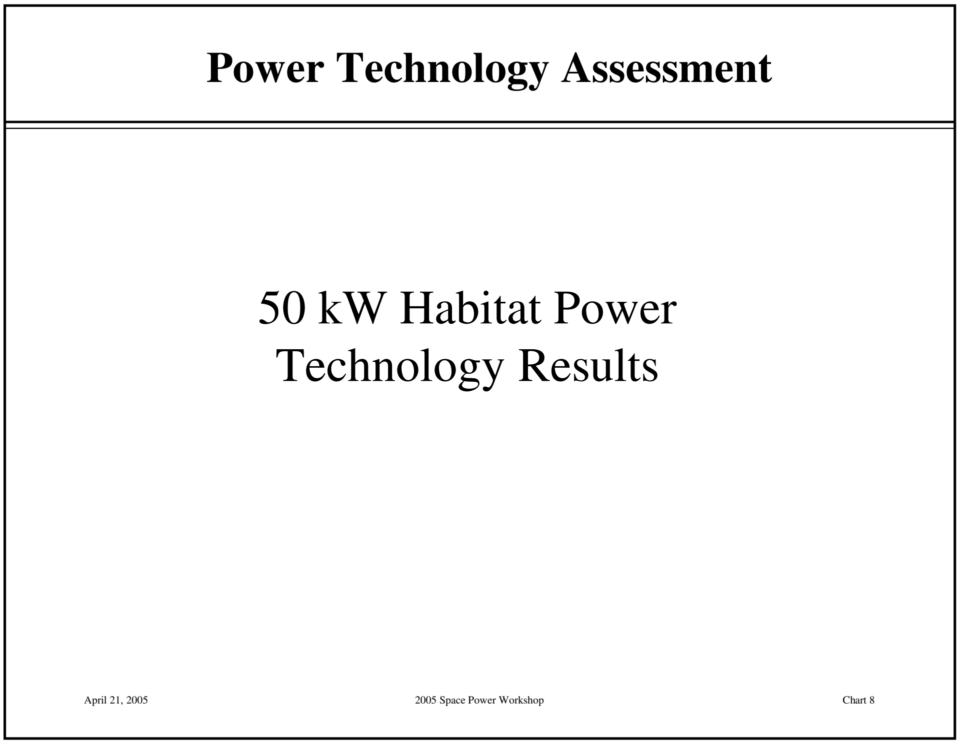
TRL 1 Basic principles observed and reported.

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

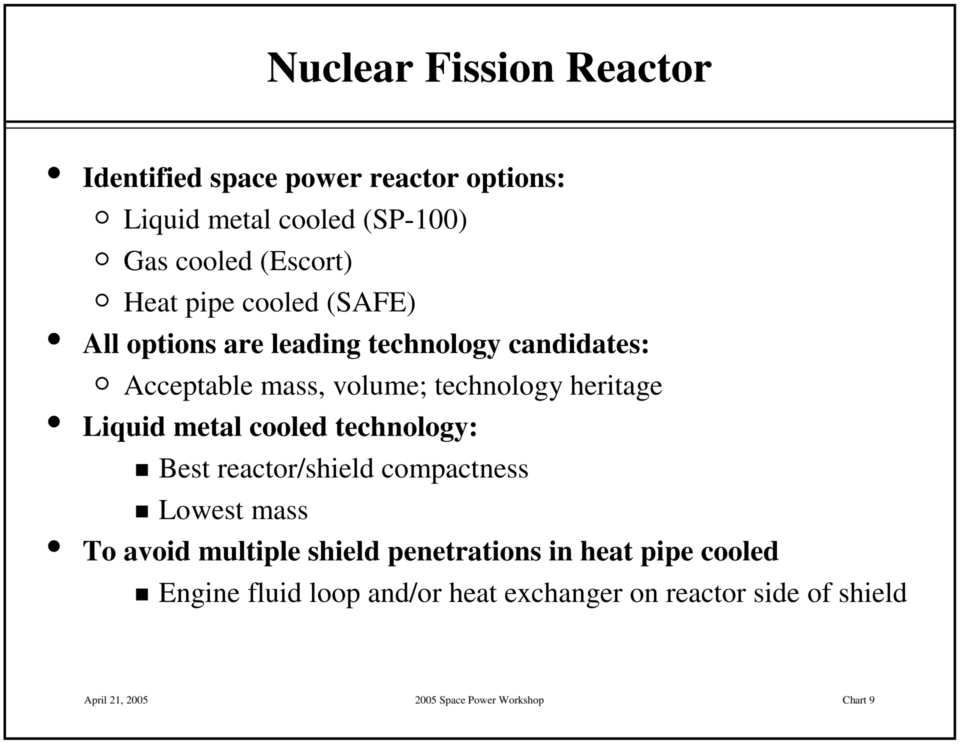
Qualitative Power Technology FOMs (3 of 16)

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



Power Technology Assessment

50 kW Habitat Power
Technology Results



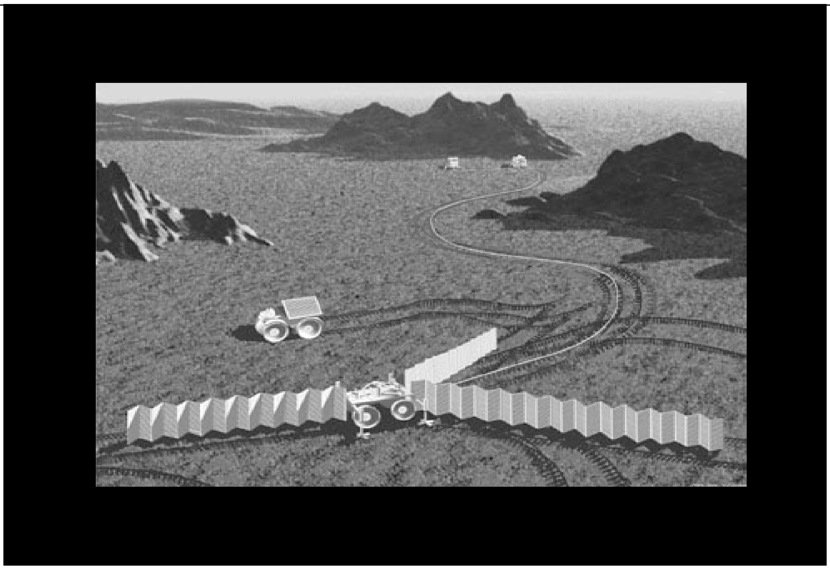
Nuclear Fission Reactor

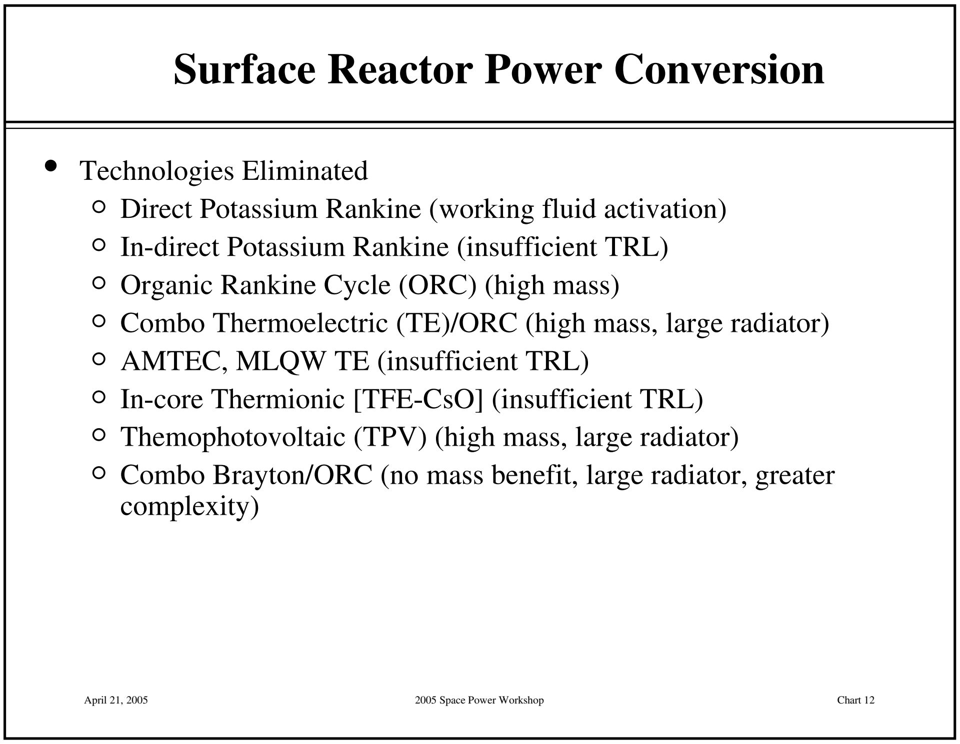
- **Identified space power reactor options:**
  - Liquid metal cooled (SP-100)
  - Gas cooled (Escort)
  - Heat pipe cooled (SAFE)
- **All options are leading technology candidates:**
  - Acceptable mass, volume; technology heritage
- **Liquid metal cooled technology:**
    - Best reactor/shield compactness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

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)

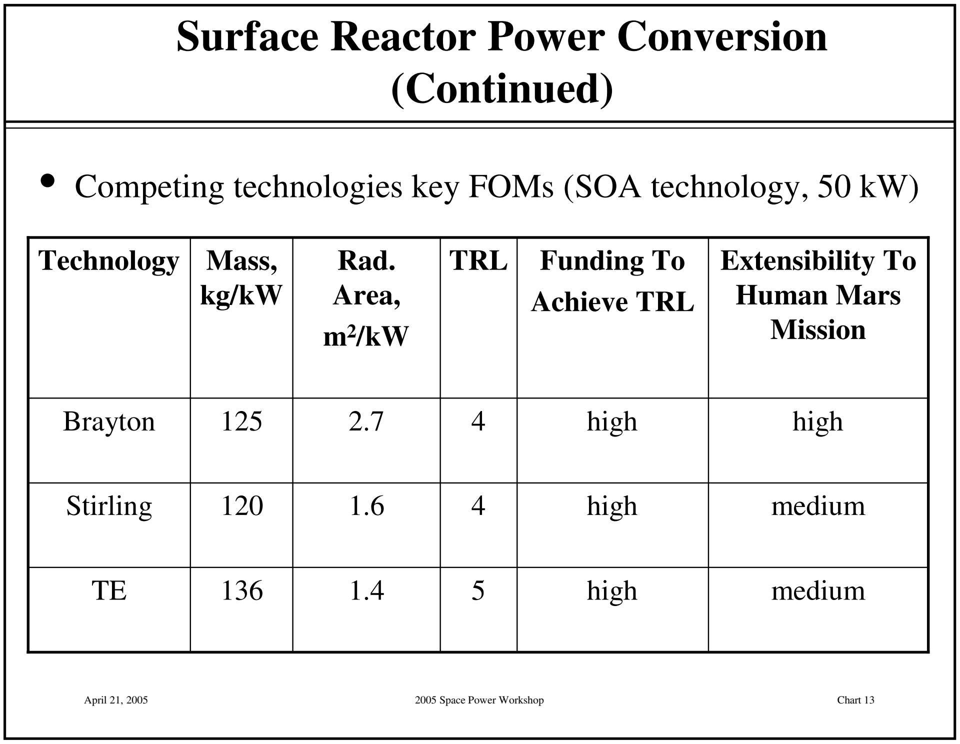
Power Technology Assessment





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)



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

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)

Collocated Solar Photovoltaic & Dynamic Power Conversion

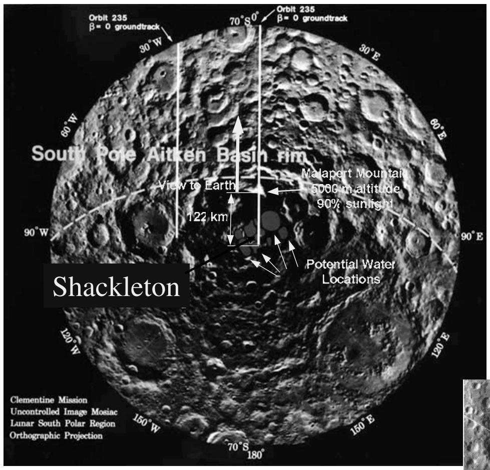
- If collocated with habitat in permanently shadowed basin
- **All solar photovoltaic & solar dynamic technologies eliminated**
  - Lack of sunlight

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).

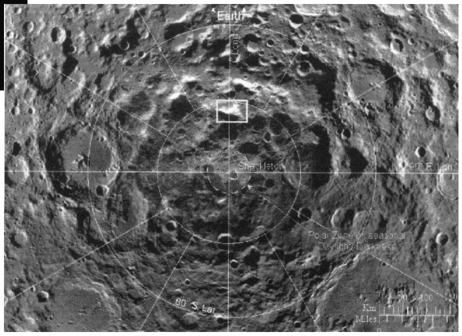
The top is a plateau approximately 10 Km^2 in area.

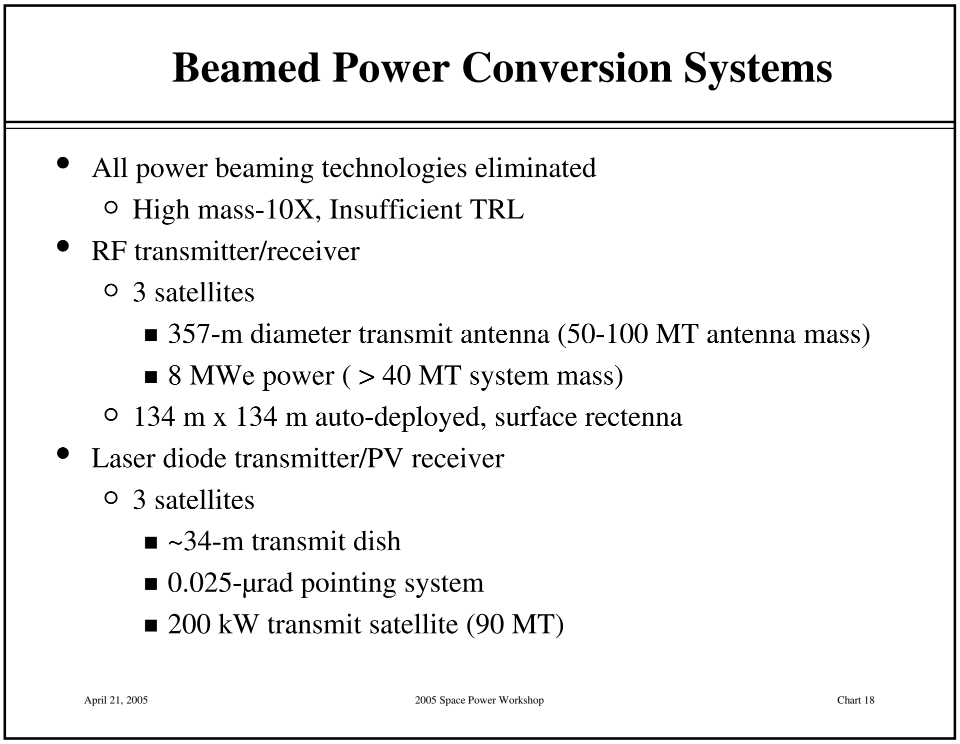
Mt. Malapert is shown in the yellow box to the right

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

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

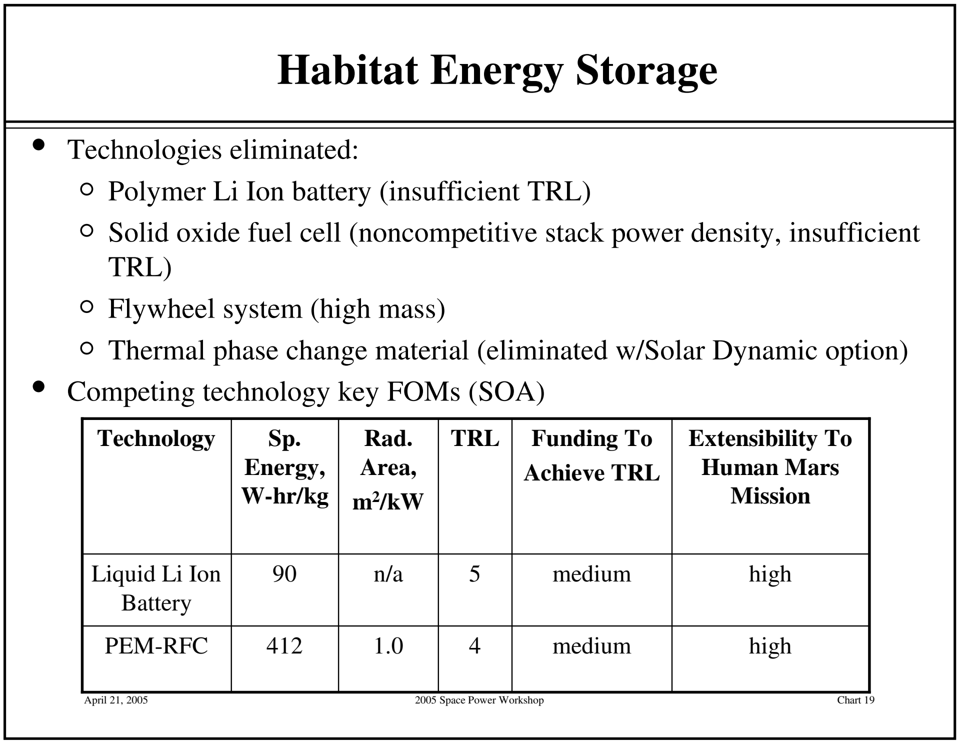
Notice the deep depressions between Mt. Malapert and the South Pole





Beamed Power Conversion Systems

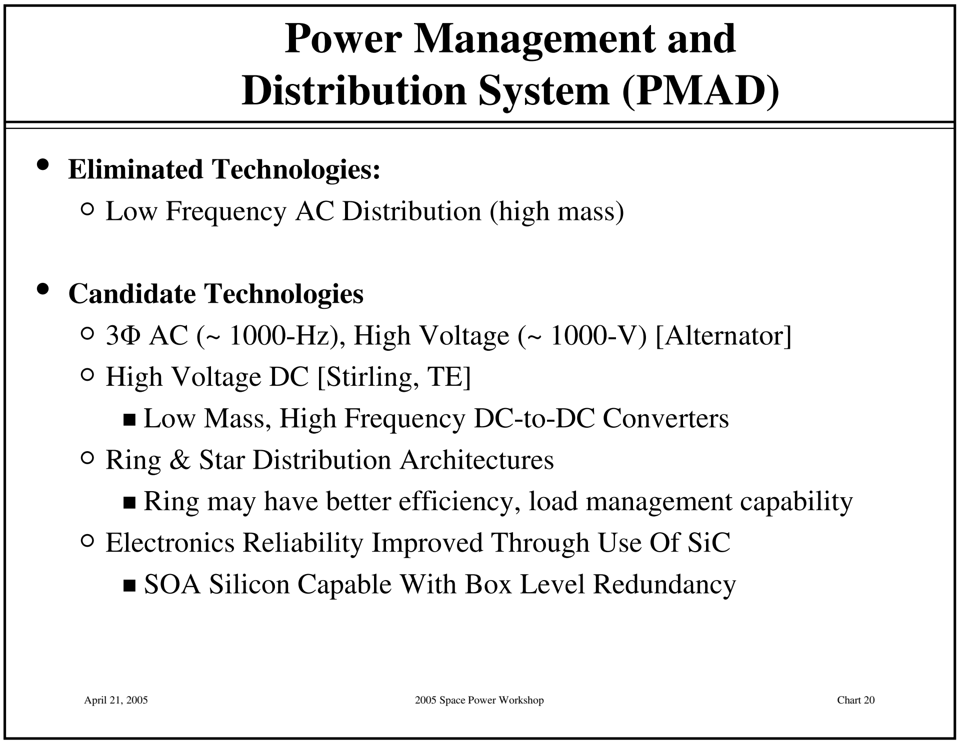
- All power beaming technologies eliminated
  - High mass-10X, Insufficient TRL
- RF transmitter/receiver
  - 3 satellites
    - 357-m diameter transmit antenna (50-100 MT antenna mass)
    - 8 MWe power (> 40 MT system mass)
  - 134 m x 134 m auto-deployed, surface rectenna
- Laser diode transmitter/PV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



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

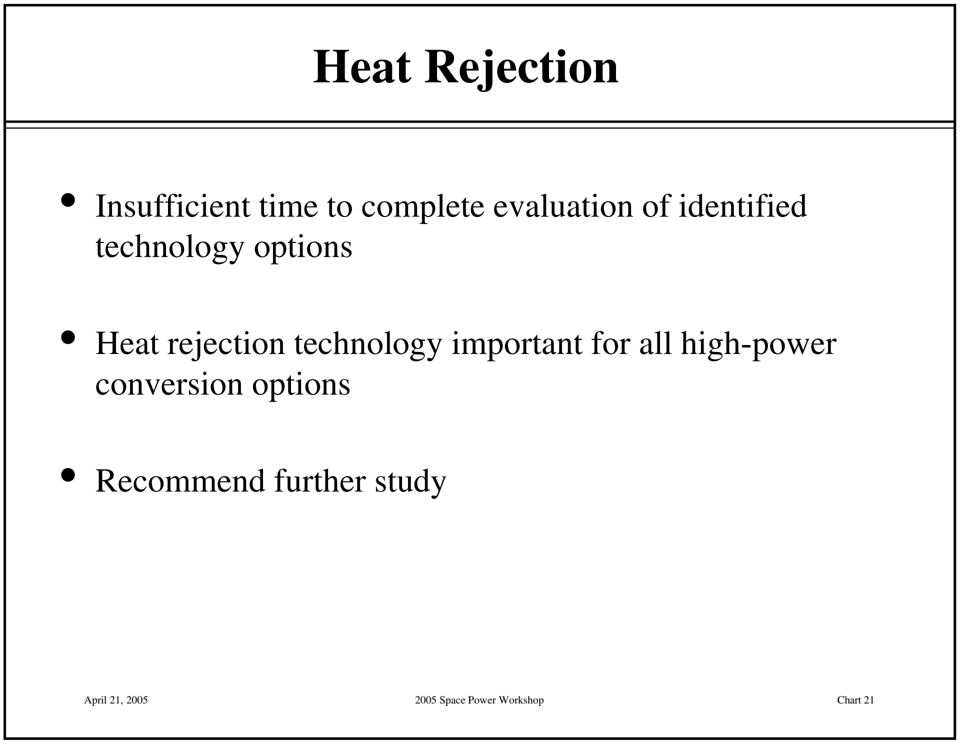


Power Management and Distribution System (PMAD)

- **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

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)

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
2nd PEM RFC	82	1.0	0.22	4	medium	medium
Primary PEM FC	40	1.0	0.14	4	medium	medium

Power Technology Assessment

Power Technology Recommendations

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

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

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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.

14. SUBJECT TERMS

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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