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A STUDY OF ELECTRIC TRANSMISSION LINES FOR USE ON THE LUNAR SURFACE

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- LUNAR ENVIRONMENT
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- ELECTRICAL ANALYSIS
- THERMAL ANALYSIS
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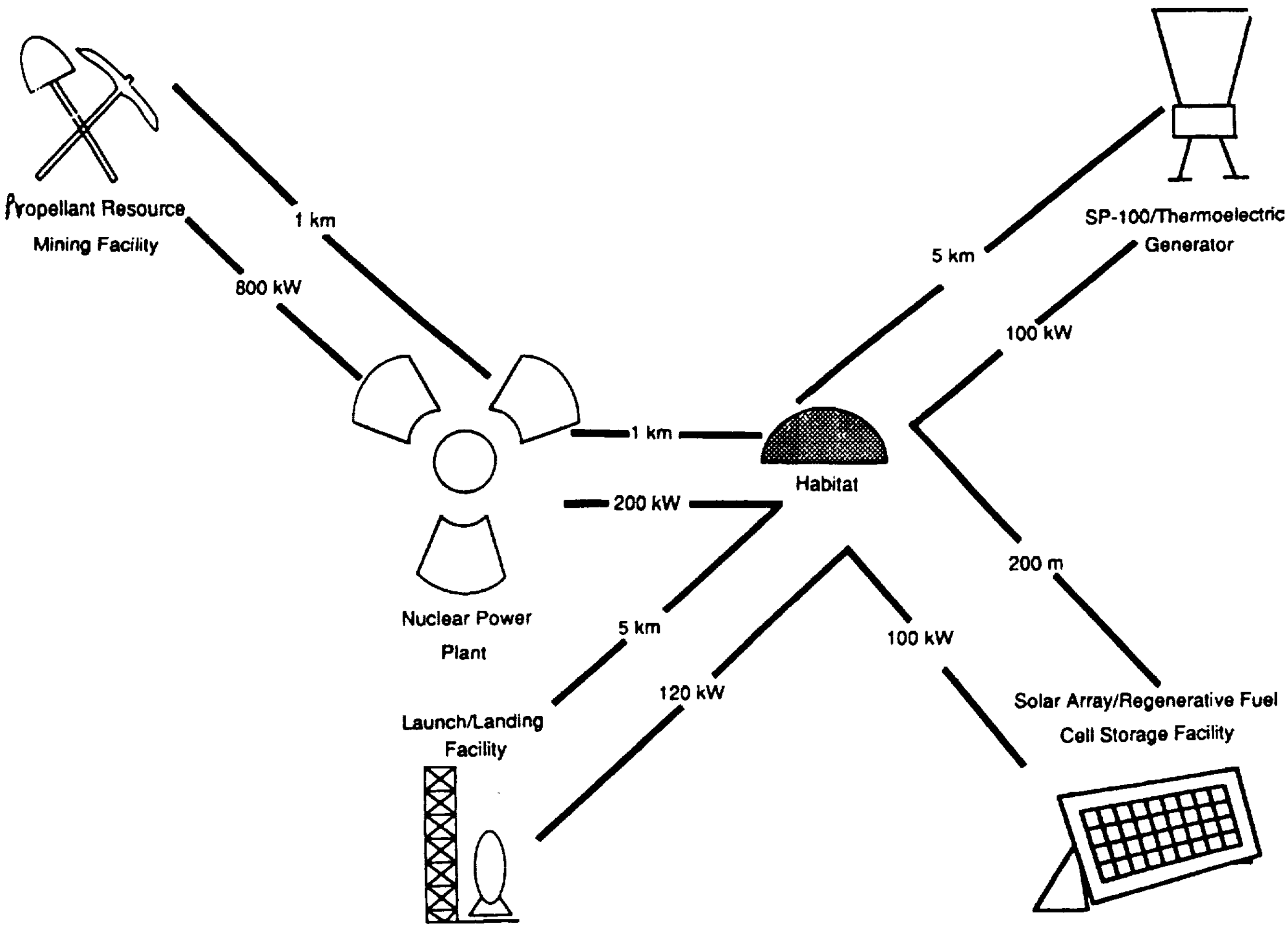

SOURCES

- **Solar/Chemical: 100 kW**
  Solar Array/Regenerative Fuel Cells

- **Nuclear (Static Conversion): 100 kW**
  Thermoelectric (SP-100)
  Thermionic (Topaz)

- **Nuclear (Dynamic Conversion): 1 MW**
  Reactor/Stirling Engine (100 Hz)
  Reactor/Brayton Engine (1 to 2 kHz)

LOADS

Habitat and Research Facilities

- Wiring requirements likely to be similar to domestic and public building requirements
- Cables will be protected from harsh environment
- Voltage less than 500 V

Launch/Landing Facility

- May involve the use of heavy equipment requiring higher operating voltages.
- Chemically hostile environment (effluents)

Resource Mining

- Mining equipment may require voltages as high as 2 to 6 kV.
- Mechanically hostile environment

Cables Likely to be Required for Lunar Base Operations

- Vacuum-insulated or Solid-dielectric-insulated (oil filled will have high mass and be difficult to maintain)

- Fixed

- wiring cables	120 - 500 V
- industrial cables	300 - 600 V
- power distribution	500 - 5 kV

- Flexible
  - must comprimise between flexibility and ease of handling and protection against mechanical damage

- Auxiliary
  - cables used for control, protection, signalling and data transmission purposes associated with power distribution and transmission systems.

- Electronic Applications
  - communication cables
  - applications in computers, automation, robotics aeorospace, and data communications
  - interconnecting cabling between individual equicpments
  - coaxial cables and twisted pair

The Lunar Environment

Pressure	— 10^{-8} torr (day) down to 10^{-12} torr (night)
Radiation	
Solar	— UV, visible, infrared, x-ray, γ-ray (1371 W/m^2)
Cosmic	— High energy particles
Charged Particles	— Solar wind
Thermal	— Lunar surface temperature (100 K to 380 K)
Dust	— Mostly fine dust and silt, some coarser sands
Contamination	— Particulate and gaseous from human activities

POWER TRANSMISSION OPTIONS

- **Power Beaming**
  - required technology will probably not be ready for initial base
  - cost of development will be expensive
- **Superconducting**
  - initial uses will probably be limited to magnetic energy storage and magnetic shielding to protect against radiation.
  - will likely require the use of liquid helium to maintain low temperatures
- **Transmission Lines**
  - reliable, proven technology
  - low cost

LUNAR BASE POWER TRANSMISSION

An early application of electrical power for lunar bases will be the manufacturing of oxygen, rocket fuel, water, and building materials from lunar soil. Powers up to 1 MW will be transported several kilometers from the sources to the loads. Transmission lines must have **minimum mass, maximize efficiency,** and **operate reliably in the lunar environment.**

TRANSMISSION LINE DESIGN

- Conductor Material
- Insulator Material
- Conductor Geometry
- Conductor Configuration
- Line Location
- Waveform
- Phase selection
- Frequency

Possible Methods of Transmission Line Insulation

- Liquid
- Gas
- Solid
- Vacuum

Electrical Insulation

Liquid and *gaseous* dielectrics are undesirable for long term use in the lunar vacuum due to a high probability of loss. Thus, insulation for high voltage transmission line will most likely be solid dielectric or vacuum insulation.

	Breakdown	Mass	Stresses
Solid Dielectric	solid dielectric puncture permanent failure	high	thermal, vacuum, radiation
Vacuum	surface flashover or vacuum arc, recoverable	low	dust contamination gas contamination

SOLID DIELCTRIC BREAKDOWN

The electrical breakdown of solid dielectrics under room temperature conditions, and under reasonable uniform field conditions is well known for terrestrial applications. However, the environmental conditions of the lunar environment are much harsher and will lead to electrical breakdown sooner or at a lower potential.

Environmental Conditions that will Influence Solid Dielectric Breakdown:

- Thermal Stress -
  Few solid dielectrics can reliably withstand the extreme temperature swings of the lunar environment.

- Vacuum Stress -
  Evaporation or chemical changes which may occur as water and gases gradually diffuse out of the material may lead to degradation of solid dielectrics.

- Radiation Stress -
  Radiation (UV, visible, x-ray, particle, etc.) damages most dielectrics.

VACUUM BREAKDOWN

Due to the high breakdown strength of vacuum and the need to limit system masses, vacuum insulation seems a logical option for high voltage lunar power systems.

Conditions which may degrade vacuum insulation:

Gas Contamination -

Gas contamination from rocket propulsion, manufacturing processes ect., will raise the pressure in the vicinity of the high field stress regions.

Particulate Contamination -

Significant particulate contamination between and on exposed conductors due to lunar dust and human activities may lead to volume or surface breakdown.

CONDUCTOR GEOMETRY

2 - wire
Coaxial
Flat

CONDUCTOR FORM

Solid
Hollow

Deployment Locations

- suspended
- below the surface
- on the surface

System Design Requirements

Power	- 100 kW and 1 MW
Waveform	- dc, 100 Hz, 1 kHz, and 10 kHz ac
Efficiency	- greater than 95 %
Distance	- 1 km
Radii	- 3 mm, 6 mm, and 9 mm

Design Variables

Voltage	- 100 V to 10 kV
Geometry	- Two-wire, coaxial, flat-plate
Location	- Above, on, or below the lunar surface
Materials	- Conductor (Al, Cu)
	- Dielectric (solid or vacuum)

Dependent Parameters

Current
Material Temp.
Electric Field Stress
Power Lost
Mass

DESIGN CONCLUSIONS

- Conductor geometry is important, especially depending on waveform.
- Operating temperature is critical and will depend on waveform, geometry, location, efficiency, and voltage.
- Higher voltages can result in significant mass, temperature, and size reductions, however, breakdown characteristics are not known well enough to predict possible breakdown conditions.
- Solid dielectrics add a substantial mass to the transmission line, especially for higher voltages.
- Operating in the lunar environment is a critical factor in transmission line design.
- It is important to study the degradation of solid dielectrics in the lunar environment, specially accounting for the synergistic effects of the vacuum, the thermal stress, and the radiation.

EXPERIMENTAL TOPICS

- The thermal characteristics of buried transmission lines.
  Study the heat conduction of simulated lunar soil.
- The thermal characteristics of suspended transmission lines.
  Study the heat radiation of conductors under a simulated lunar environment.
- The electrical characteristics of the lunar soil.
  Study the conduction and breakdown characteristics of on-the-surface and buried conductors.
- Volume and surface breakdown in the lunar environment.
  Study the motion and effects of lunar dust in electric fields.
- Electrical characteristics of lunar dust.
  Study the motion and effects of lunar dust in electric fields.
- Degradation of solid dielectrics in the thermal, radiation, and vacuum.
  Study the stress factors individually and synergistically for many candidate dielectrics.

ADDITIONAL CASES

- Stranded cable
- Litz wire
- Single Phase vs Three Phase

STRANDED CABLE

At low voltage/low frequency, stranding and spiraling of the line is done primarily to increase the flexibility of the line, thus improving the ease of transportation and deployment of the cable.

- Stranding creates a slight increase in weight and electrical resistance. This increase will be proportional to the increase in length caused by the spiraling.
- Typically conductors are stranded for wire diameter greater than 4/0 Awg.

LITZ WIRE

Litz wire consists of individually insulated strands of wire woven together such that each strand tends to take all possible positions in the cross section of the entire conductor.

- The primary benefit of Litz conductor is the reduction of a.c. losses. (the resistance ratio a.c. to d.c. is approximately one).
- The primary design concern is the operating frequency. It determines both the construction of the cable and the wire gauge of the individual strands.
- Accurate thermal analyses will be difficult.
- Litz configurations:
  - round
  - braided
  - rectangular
  - square

SINGLE PHASE VS THREE PHASE

- 1-Ø, 3-wire and 3-Ø, 4 wire designs have the same maximum possible power transmitted. (Assuming an equal amount of conductor material is used to both cases).
- 1-Ø, 3-wire will continue to operate at reduced power should one line fail.
- 3-Ø is less pulsating. (This is advantages for motor loads because it produces more uniform torque).
- 3-Ø equipment is physically smaller in size than similar single phase equipment.
- Three 1-Ø lines can be derived from 3-Ø giving it more distribution flexibility.
- The addition of more lines will increase the mass due to the additional insulators required.
- Generating 3-Ø may require more equipment and be more complicated than generating 1-Ø from the proposed sources.