Planetary Drilling and Resources at the Moon and Mars

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Planetary Drilling and Resources at the Moon and Mars

Drilling on the Moon and Mars is an important capability for both scientific and resource exploration. The unique requirements of spaceflight and planetary environments drive drills to different design approaches than established terrestrial technologies. A partnership between NASA and Baker Hughes Inc. developed a novel approach for a dry rotary coring wireline drill capable of acquiring continuous core samples at multi-meter depths for low power and mass. The 8.5 kg Bottom Hole Assembly operated at 100 We and without need for traditional drilling mud or pipe. The technology was field tested in the Canadian Arctic in sandstone, ice and frozen gumbo.

Planetary resources could play an important role in future space exploration. Lunar regolith contains oxygen and metals, and water ice has recently been confirmed in a shadowed crater at the Moon’s south pole. Mars possesses a CO₂ atmosphere, frozen water ice at the poles, and indications of subsurface aquifers. Such resources could provide water, oxygen and propellants that could greatly simplify the cost and complexity of exploration and survival.
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Jeff George is a project manager, systems engineer, technologist, and advanced mission planner at the NASA Johnson Space Center in Houston, TX. His responsibilities include developing mission architectures for human exploration of the Moon and Mars; leading the NASA/JSC Nuclear Systems Team to plan, assess and develop space nuclear power and propulsion technologies; and serving as Mission Architect for the planned RESOLVE lunar resource mission. Jeff led the successful collaboration of NASA and Baker Hughes Inc. to develop a low mass and power drilling technology through two prototype cycles and field testing in the Canadian High Arctic. Jeff earned his B.S. and M.S. in Nuclear Engineering from Texas A&M University.
Contents

30-45 min

40 charts

• Introduction
  • 4 charts

• Planetary Drilling
  – Why Drill? 2 charts
  – Apollo Drilling Experience 7 charts
  – NASA/Baker Hughes Mars Drill Prototype 5 charts
  – Arctic Field Testing 9 charts
  – Rover Drilling & Accomplishments 3 charts

• In-Situ Resources at the Moon and Mars
  • 9 charts
  – Type, Use and Value 3 charts
  – Production and Conversion 4 charts
  – Prospecting and Missions, RESOLVE 2 charts

• Summary
  • 1 chart
**Why Drill?**

**Mars “Follow the Water” Strategy**

- **Common Thread**
  - **W**ater
  - **A** life
  - **T**rue
  - **E**ven
  - **R**epresentation

- **Subsurface liquid water best chance of finding Martian life**
- **Cycling between subsurface and atmosphere, sedimentary record**
- **Water is critical resource for HEDS and permanent Mars presence**

- **Prepare for Human Explorations**
  - Understand the Potential for Life Elsewhere in the Universe
  - Understand the Relationship to Earth’s Climate Change Processes
  - Understand the Solid Planet: How It Evolved
  - Develop the Knowledge & Technology Necessary for Eventual Human Exploration
Mars Subsurface Scientific Objectives

**Surficial processes:** min., petrology, physical props. (density, perm.), weathering/erosion processes, impact gardening, gradient in surficial oxidant, EM

**Pre-weathering processes**
- sedimentation processes, stratigraphy
- past environments, history of volatiles
- Geophysics: Heat flow, thermal state, seismic

- Organic geochem below oxidized zone
- presence of ice?

- Bedrock: Rock-forming processes, history

- Sample permafrost or massive, segregated ground ice, volatile hydrates

- Access Liquid Acquifers?

100’s–1000’s m?
Apollo Lunar Surface Drill (ALSD)

- First “Cordless” Drill (?)
- Martin-Marietta, Black&Decker
- Handheld drive unit
  - Battery powered
  - ~430 - 500 W
- Rotary-percussion action
  - 280 rpm
  - 2270 bpm
  - 40 in-lb / blow
- Coring Bit:
  - 6 cm long x 2 cm ID
  - Steel body + 5 brazed tungsten carbide tips
- Drill stem:
  - 40cm long, 2.5cm OD, 2.0cm ID
  - Titanium alloy
  - External auger flights
- Carrier & Treadle/removal tool
- Total depth capability = 3.0 m
- Total system mass = 13.4 kg
Apollo Lunar Drilling Results

• Flew on Apollo 15, 16, 17
• Purpose:
  – Acquire core samples
  – Emplace heat flow thermocouples
  – Neutron probe
• ~5-15 minutes to drill each hole
• Astronauts learned to:
  – “Hold-back” as drill advanced
  – Clear cuttings to surface before remove
• A-15 drill stem very difficult to remove
  – Both astronauts & sprained shoulder
• Redesign & “treadle/jack” aided 16, 17
• 7.6 m cum. Exc. recovery & stratigraphy
• Regolith: jagged, interlocked agglutinates
• Top few cm’s: “fluffy” unconsolididated
• Deeper cm’s: closely packed, 1.6-2.1 g/cc.
• Hope: Cores would reflect slow evolution history of surface
• Cores surprisingly homogenous- no distinct ancient surfaces found
• Deepest core last exposed ~1B yr ago
Other Apollo Sampling Tools

Fig. 26. Tools of the type used on Apollo 11 (L to R): lighter weight hammer, gnomon, shorter tongs, shorter extension handle, box-shaped scoop. The extension handle was used with the hammer and the scoop (NASA photo S69-31860).

Fig. 72. Apollo 16 Lunar Sample Return Container upon opening in the Lunar Receiving Laboratory. The box contains a large rock, several documented sample bags with the fold-over aluminum tabs, and a 4-cm diameter drive tube (NASA photo S72-36984).
Tongs & Rake
Rake
**Vision (why):** Explore Mars’ subsurface, to understand history, climate, life, and resources.

**Mission Statement (what):** Develop a deep drilling and sample acquisition capability.

**Project Major Goals:**

**Goal I:** Advance Drill to TRL=4 (System in lab environment)

**Goal II:** Advance Drill to TRL=5 (System in field environment)

**Goal III:** Participate in M/ADD Project and demonstrate in Arctic

**Goal IV:** Demonstrate Rover-deployed drilling

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**“Mark I” Mars Drill Project Objectives & Requirements**

**“Mark II” Mars Drill Project Objectives & Requirements**
NASA / Baker Hughes Inc. Mars Drill
Space Act Collaboration

- **NASA / Johnson Space Center / EX**
  - Project Management
  - System Design, Integration, and Test
  - BHA Assy (Anchor, Force-on-Bit, Drive Motor)
  - Surface Support Assembly
  - Control Electronics (Hardware)

- **Baker Hughes Incorporated**
  - Industry Partner
  - Drilling Mechanics
  - Ops. Expertise
  - BHA Auger, Bit, Core Break/Trap S/A’s

- **NASA/JSC / SCOUT Rover**
  - Mobility; Rover/Drill Demo

- **NASA/JSC / EC Rover**
  - Mobility; Rover/Drill Demo

- **NASA/JSC / EX ACES Van**
  - Remote Operations Demo

- **NASA/JSC / ARES**
  - Moon Science Objectives
  - Moon Subsurface Environment

- **NASA / Ames Research Center**
  - PI for Code S/ASTID “M/ADD” Project
  - Automation

- **Lunar and Planetary Institute**
  - Mars Science Objectives
  - Mars Subsurface Environment

- **UC Berkeley**
  - Fundamental Research
  - Component Laboratory Testing
  - Modeling and Simulation

- **University of Texas**
  - Leadership & Outreach

- **MacGill University; University of Toronto**
  - Arctic Multidisciplinary Science
  - Sample Contamination
Challenges of Drilling on Mars:

- Achieving Depth
- Limited Mass
- Limited Power
- Aseptic Sampling
- No Drilling Fluids:
  - Cuttings Removal
  - Heat Transport
  - Sample Contamination

Our Approach:

Drilling Function
- Sample acquisition
- Comminution
- Cuttings Removal
- Torque
- Force-on-bit
- Power Transmission
- Cooling

Technical Approach
- Dry
- Rotary Coring Bit
- Downhole Motor
- Wireline
- Bailing
- Borewall Anchoring
- Internally applied Force-on-bit

Features
- Continuous Core & Cuttings Record
- Low Sample Contamination
- Low Mass
- Low Power
- Deep capable
- Modest Penetration Rates
- Sensitive to Formation Stability
**Coring / Bailing Operational Sequence**

**A** – Initial Deployment, Tool is Lowered to tag the Bottom of the Drill Hole

**B** - Anchor Module is Expanded against bore

**C** – The winch pulls up on the wireline, setting and latching the FOB spring

**D** – Anchor is Contracted; Tool is lowered to tag the Bottom of the drill hole to initiate drill bite.

**E** – The Anchor is expanded, drill motor is started and the FOB Spring is released so that drilling force is placed on the rotating drill bit.

*Repeat from C, D, E to complete drill trip*
Mk2 Drill Elements & Characteristics

• **Bottom Hole Assy (BHA):**
  – **General**
    • Length: Approx. 7 feet
    • Diameter: approx. 1.75 inches
    • Weight: ~30 lbs
  – **Electrical**
    • Continuous Power: 100 W
    • Peak Power: 200W
    • Max. Voltage sent to BHA: ~30VDC
  – **Mechanical**
    • Max. Force-on-Bit: -200 to +200
    • Internal Stroke of AFOB Spring: ~0.25 inch
    • Drill Bit/Auger RPM: 0-225

• **Umbilical / Tether** (Power, Data, Recovery)

• **BHA Control Box (yellow box)**
  – Input Power: 120 VAC @ (.8 amps nominal)
  – Weight: 35 lbs

• **Surface Equipment (weight)**
  – Rock Support Fixture: ~25 lbs
  – Spud Tube: ~10 lbs

• **Laptop**: Panasonic Toughbook
• **Software**: Labview (Logging & Control)
2006 Field Testing

Eureka, Ellesmere Island, Canada.
Field Test - Specific Ops
Ellesmere Island, Canadian High Arctic
2006 Site Locations

Drop-Off Point at Road
(~300 feet below in elevation)

Site 1: Sandstone

Site 2: Ice Wedge
Critters
2004 Chris-Rock Cores & Bites

- Second Sandstone Bore, Eureka, Sept. 2004
  - Bore Depth = 21.2” (0.5 m)
  - Total Core lengths = 21” (0.5 m)

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<td>Length:</td>
<td>2.8”</td>
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<tr>
<td>ROP:</td>
<td>3.4”/hr</td>
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<table>
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<th>Core #:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<tr>
<td>Length:</td>
<td>2.6”</td>
<td>3.5”</td>
<td>5.4”</td>
<td>3.1”</td>
<td>1.4</td>
<td>1.2</td>
<td>1.1</td>
<td>2.3”</td>
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New Bit, Reaming

Sunday

Tuesday
## Field Performance: 2004 vs 2006

<table>
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<tr>
<th>PERFORMANCE:</th>
<th>2004</th>
<th>2006</th>
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<tbody>
<tr>
<td>Max. Depth in Sandstone</td>
<td>0.5 meter</td>
<td>2 meters</td>
</tr>
<tr>
<td>Cum. Depth in Sandstone</td>
<td>1.1 meters</td>
<td>2 meters</td>
</tr>
<tr>
<td>Depth in Ice</td>
<td>2 meters in iceberg (1)</td>
<td>1 meter in ice wedge (2)</td>
</tr>
<tr>
<td>Average Drilling Rate</td>
<td>3.6 in/hr</td>
<td>8.1 in/hr</td>
</tr>
<tr>
<td>Average Drilling Power</td>
<td>60-120 Watts electric</td>
<td>60-175 Watts electric</td>
</tr>
<tr>
<td>Time on Bottom</td>
<td>724 min.</td>
<td>573 min.</td>
</tr>
<tr>
<td>Total Number of SS cores</td>
<td>16 cores</td>
<td>24 cores</td>
</tr>
<tr>
<td>Total Number of Drill days</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

(1) With MK IIa drill motor (manual force-on-bit)
(2) With MK IIb auger/drill bit (manual force-on-bit)
Rover/Drill System Key Elements

- Scout Rover
- Mk2b Drill (BHA)
- Rover Support Assy
  - Spud Tube
  - Linear Actuator
  - Pitch, Roll Actuators
  - Inclinometer
  - Stabilization Jacks
  - Custom Bumper
- Infrared Camera
- Visual Camera
- Also (not shown):
  - Drill Control
  - RSA Control
  - Laptop & Labview S/W
  - Operators
JSC/BHI Mars Drill Accomplishments

• Successfully Achieved Major Project Goals:
  – Mk1 Prototype Development, Lab Testing, and “TRL-4” Demo
  – Mk2 Prototype Development, Field Testing and “TRL-5” Demo
  – Arctic Field Testing and M/ADD Collaboration
  – Mobile Rover-deployed Drilling and Remote Command/Control

• Developed/Demonstrated Novel Approach for Planetary Drilling:
  – Dry, rotary, coring, wireline, bailing Bottom Hole Assembly
  – Low Mass: 8.5 kg BHA
  – Low Power: 100 watts-electric operation
  – Depth: Multiple meters, extensible to 10’s+ meters
  – Asceptic core samples: 2.5 cm dia by 15 cm, continuous record
  – Modest Force-on-Bit: 387 N (87 lbf)
  – Rotary Speeds: 100-120 rpm
  – Modest Rate-of-Penetration: 20 cm/hr rate of penetration
  – 2 m depths demo’d in Sandstone, Ice, Unconsolidated Sand
  – Five different Drill Bit technologies explored; Multiple Auger families
  – Applicable to Mars or Moon, and Robotic or Human Missions
Settling the West

We wouldn’t have gotten far if we couldn’t use the local resources

HAYBURNER ANALOGY

- MULE CONSUMABLES
  - HAY: 15 LB/MULEDAY
  - WATER: 58 LB/MULEDAY
  - OXYGEN: 12 LB/MULEDAY
  - TOTAL: 85 LB/MULEDAY

- 6 MULES CAN PULL LIGHT WAGON WITH 2000 LB MAXIMUM LOAD 25 MILES/DAY

- (2000 LB) x (25 MILES/DAY) = RANGE
  - (6 MULES) x (85 LB/MULEDAY)

- MAXIMUM RANGE = 100 MILES
Space Resources

Four major resources on the Moon:
- **Regolith**: oxides and metals
  - Ilmenite 15%
  - Pyroxene 50%
  - Olivine 15%
  - Anorthite 20%
- Solar wind volatiles in regolith
  - Hydrogen 50 – 150 ppm
  - Helium 3 – 50 ppm
  - Carbon 100 – 150 ppm
- **Water/ice** and other volatiles in polar shadowed craters
  - 1-10% (LCROSS)
  - Thick ice (SAR)
- Discarded materials: Lander and crew trash and residuals

Three major resources on Mars:
- **Atmosphere**:
  - 95.5% Carbon dioxide,
  - 2.7% Nitrogen,
  - 1.6% Argon
- **Water in soil**: concentration dependant on location
  - 2% to dirty ice at poles
- Oxides and metals in the soil

~85% of Meteorites are Chondrites

**Ordinary Chondrites** 87%
- FeO:Si = 0.1 to 0.5
- Fe:Si = 0.5 to 0.8
- Source metals (Carbonyl)

**Carbonaceous Chondrites** 8%
- Highly oxidized w/ little or no free metal
- Abundant volatiles: up to 20% bound water and 6% organic material

**Enstatite Chondrites** 5%
- Highly reduced; silicates contain almost no FeO
- 60 to 80% silicates; Enstatite & Na-rich plagioclase
- 20 to 25% Fe-Ni
- Cr, Mn, and Ti are found as minor constituents

**Water is the Key Resources**
- Life Support
- Rocket Propellant
- Radiation Shielding

Easy source of oxygen (Carbothermal)
Space Resource Utilization Changes
How We Can Explore Space

Mass Reduction

- >7.5 kg mass savings in Low Earth Orbit for every 1 kg produced on the Moon
- Chemical propellant is the largest fraction of spacecraft mass

Risk Reduction & Flexibility

- Provides ‘safe haven’ capabilities for aborts and delayed cargo resupply
- Radiation and landing/ascent plume shielding
- Increases flexibility and options for contingency and failure recovery operations
- Reduces dependence on Earth

Enables Space Commercialization

- Provides infrastructure, technologies, and market to support space commercialization
- Propellants, energy, metals, and manufacturing feedstock

Cost Reduction

- Allows reuse of transportation systems
- Reduces number and size of Earth launch vehicles

Expands Human Presence

- Increases Surface Mobility & extends missions
- Habitat & infrastructure construction
- Propellants, life support, power, etc.

Goal: ‘Close the Loops’
- Common fluids, pressures, quality, and standards
- Common storage, distribution, and interfaces
- Common technologies and hardware for flexibility and reduced DDT&E
NASA ISRU Development Areas

Excavation for O₂ Extraction  Site Preparation - Area Clearing

O₂ Production / Volatile Extraction from Soils

Resource Prospecting / Mapping  Surface Sintering / Hardening
**Lunar Processing – Oxygen & Metal Extraction**

### Hydrogen Reduction of Regolith

1. **Heat Regolith to >900 °C**
2. **React with Hydrogen to Make Water**
3. **Crack Water to Make O₂**

\[
\text{FeO} + \text{H}_2 \rightarrow \text{Fe} + \text{H}_2\text{O}; \quad \quad \quad 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2
\]

**PILOT**
- 250 kg O₂ per year

**ROxygen**
- Water Electrolysis Module
- O₂ Cryo Tank

**Two Fluidized H₂ Reduction Reactors**
- 10 kg/batch each (1050 °C)

**Rotating H₂ Reduction Reactor**
- 17 kg/batch

**Regolith reactor exhaust**
- 660 kg O₂ per year

**Regolith hopper/auger lift system**
- 2

**Carbothermal Reduction of Regolith**

1. **Melt Regolith to >1600 °C**
2. **React with Methane to CO**
3. **Convert CO to Methane & Water**
4. **Crack Water to Make O₂**

\[
\text{SiO}_4 + \text{CH}_4 \rightarrow \text{CO} + 2\text{H}_2 + \text{Si}; \quad \quad \quad \text{CO} + 3\text{H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O}; \quad \quad \quad 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2
\]

**Molten Electrolysis of Regolith**

1. **Melt Regolith to >1600 °C**
2. **Apply Voltage to Electrodes To Release Oxygen**

**Lift System and Auger Loading**

**Regolith Storage**
- 1 day

**Regolith Reduction Chamber**

**Lift System and Auger Loading**

**Regolith Storage**
- 1 day

**Regolith Reduction Chamber**

**Lift System and Auger Loading**

**Regolith Storage**
- 1 day

**Rotating H₂ Reduction Reactor**
- 17 kg/batch
Proposed “RESOLVE” Lunar Polar Ice/Volatile Prospecting Mission

- Total Station-Relative Navigation (CSA)
- Communications (NASA)
- Lander (NASA)
- Situation Awareness Camera (NASA)
- Situational Awareness Camera & Lights (CSA)
- DESTIN Drill System (CSA)
- Rover Communications (CSA)
- Navigation & Situational Awareness Cameras & Lights (CSA)
- Solar Array (NASA)
- Artemis Jr. Rover (CSA)
- LAVA Gas Chromatograph/Mass Spectrometer (NASA)
- Neutron Spectrometer (NASA)
- Near Infrared Spectrometer (NASA)
- Avionics & Software (CSA & NASA)
- OVFN Sample( Heating Unit (NASA)
- Mission Control, Timeline, Traverse & Data Display Software (NASA)
Mars Resources, Processes & Products

MARS RESOURCES

ATMOSPHERE

Carbon Dioxide (CO₂) 95.5%  
Nitrogen (N₂) 2.7%  
Argon (Ar) 1.6%  
Oxygen (O₂) 0.15%  
Water (H₂O) <0.03%

SOIL

Fe₂Mg₂Si₂O₈  
Fe₂O₃  
FeSiO₃

SURFACE VOLATILES

Polar Water (H₂O) TBD  
Perma Frost (H₂O) TBD  
Frozen CO₂ TBD

COMPLEX HYDROCARBON MANUFACTURING

\[ CO₂ + 2H₂ \rightarrow CH₄ + H₂O \]

METHANE REFORMER

\[ CO + 3H₂ \rightarrow CH₄ + H₂O \]

WATER ELECTROLYSIS (WE)

\[ 2H₂O \rightarrow 2H₂ + O₂ \]

SABATIER CATALYTIC REACTOR (SR)

\[ CO₂ + 4H₂ \rightarrow CH₄ + 2H₂O \]

ZIRCONIA SOLID OXIDE CO₂ ELECTROLYSIS (ZE)

\[ 2CO₂ \rightarrow 2CO + O₂ \]

SABATIER CATALYTIC REACTOR (SR)

\[ CO₂ + 4H₂ \rightarrow CH₄ + 2H₂O \]

METHANE REFORMER

\[ CO + 3H₂ \rightarrow CH₄ + H₂O \]

WATER ELECTROLYSIS (WE)

\[ 2H₂O \rightarrow 2H₂ + O₂ \]

HIDROTERMAL REDUCTION

\[ Fe₂Mg₂Si₂O₈ + 2H₂ \rightarrow Mg₂SiO₄ + SiO₂ + 2H₂O + 2Fe \]

CARBOTERMAL REDUCTION

\[ Fe₂Mg₂Si₂O₈ + 6CH₄ \rightarrow 2MgO + 6CO + 12H₂ + 2Fe + 2Si \]

ZIRCONIA SOLID OXIDE CO₂ ELECTROLYSIS (ZE)

\[ 2CO₂ \rightarrow 2CO + O₂ \]

SABATIER CATALYTIC REACTOR (SR)

\[ CO₂ + 4H₂ \rightarrow CH₄ + 2H₂O \]

CARBOTERMAL REDUCTION

\[ Fe₂Mg₂Si₂O₈ + 6CH₄ \rightarrow 2Mg + 6CO + 12H₂ + 2Fe + 2Si \]

THERMAL VOLATILE EXTRACTION

Nasa/Jsc/Ep/Jag
Mars MSL Rover “Curiosity”

Sedimentary Conglomerate?
- Fractured outcrop w/ clean exposed surface
- Rounded gravel clasts few cm's in size
- White matrix material
- Gravel sized rocks have eroded off
**Summary**

*Planetary Drilling* is a key technology for future space exploration

- Science: geology, climate history, astrobiology
- Resource prospecting
- Unique requirements drive unique design solutions

*Planetary Resources* enable robust human space exploration

- In-situ production of oxygen, water, propellants, shielding, etc.
- “7.5-to-1” gear ratio for the Moon
- **Moon:**
  - Regolith \(\rightarrow\) Oxygen
  - Polar shadowed craters \(\rightarrow\) Water ice
- **Mars:**
  - Carbon dioxide atmosphere \(\rightarrow\) Oxygen
  - Poles \(\rightarrow\) Water ice
  - Aquifers?