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Introduction

- Next missions targeted at very high/low latitudes are expected to find regolith characterized by the presence of ‘important’ fractions of volatile/ices among which water ice.

- As far as Drilling operations, water ice acts as a bonding mechanism between regolith particles and it certainly may have an important effect on the strength of the regolith itself.

Soil strength trend with respect to ice concentration (left-Tsytovich, 1973, Fig. 80) and soil temperature (right-from a presentation of Kris Zacny)
Main *sampling requirements* given for the Drill System development are summarized as:

- **sampling depth**: selectable down to 2 meters
- **sample size**: \( d \approx 10 \text{ mm}, \ L = 20-30 \text{ mm} \)
- ‘sample integrity’
- *recording temperature history*

Concerning *soil characteristics* the following requirements are taken:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value (referred @ 2 m depth)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bulk density</strong></td>
<td>g/cm(^3)</td>
<td>2 (2.24 with 11.9% wt of water ice)</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>K</td>
<td>120</td>
</tr>
<tr>
<td><strong>Thermal conductivity</strong></td>
<td>W/(cm*K)</td>
<td>2.5*10(^{-2})</td>
</tr>
<tr>
<td><strong>Water content</strong></td>
<td>%</td>
<td>11.9 (saturation)</td>
</tr>
<tr>
<td><strong>UCS</strong></td>
<td>MPa</td>
<td>95</td>
</tr>
</tbody>
</table>
Concerning sample(s) integrity:
• integrity of physical form (e.g. association of volatiles with soil components, avoiding phase transitions, stratigraphy/layering);
• quantitative integrity (e.g. minimize volatiles loss)
• chemical contamination (i.e. introduction of foreign material into sample; sample-to-sample cross contamination)

Concerning the minimization of volatile loss, conditions of ‘temperature increase’, ‘max allowed time’, sample size, need be duly considered and understood in the frame of state diagrams and sublimation cure profiles, for example:
Drill preliminary configuration

The Drill System is now conceived as formed by two main elements

- **the Drill** proper it is based on a *single string driven by a roto-hammer mandrel* plus a translation stage and is capable to reach selectable depth ranging from surface down to 2 meters
- **the Positioner** now conceived as a double degree of freedom device
Drill preliminary configuration

- Drill translation guides
- Hammer actuator embedded inside the mandrel
- Spider mechanism to support drill rod
- Drill translation screw
Drill preliminary configuration

- Mandrel case
- Hammer actuator
- EC40+GP42 motoreducer
- Slip ring
- Rotation motor support
- Mounting interface for future translation guides
- Crown
- Pinion
- Bearings shaft
- Crown hub
Hammer actuator

- Embedded on top of the mandrel assembly
- Operating in the range of 10 / 15 Hz
- Energy involved for each strike in the order of 2J
- Operating in resonance mode
Hammer indexing

- Indexing can be defined as the front bit rotation angle advance between two subsequent strikes.
- Should be selected such to render efficient, the ‘chisel’ strike on the surface:
  - A too low indexing imply extra unused energy injected into the soil
  - A too large indexing imply a low efficiency of the strike action

![Diagram: Predivus strike, New strike, Damaged area (in red), Schematics only, Bit advance, Likely 'too low indexing', Likely 'too high indexing', 'Acceptable indexing']
Sampling tool (L-GRASP)

- Designed to cope with hard saturated material and loose dry soil
- Actuated by a motoreducer invisible to hammer percussive action
- Two embedded temperature sensors (sampling chamber and bit) to monitor the material temperature variations
**Sampling tool: Operations**

1. **Drilling**

2. **Coring (reference position)**

3. **Pinching**

   *When coring, spikes occlude as much as necessary the tunnels of the teflon guide to prevent sample material intrusion.*
Sampling tool: discharging the sample

When pushing out the sample, the tunnels acute angles (w.r.t to moving direction) naturally prevent sample material entering the empty spaces.
**Drilling depth vs vertical envelope**

### Table 6 - Design parameters

<table>
<thead>
<tr>
<th>Distance</th>
<th>Description</th>
<th>Value [mm]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Upper plate thickness</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Mandrel height</td>
<td>310</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Spider height</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Drill translation blocking height + Lowe plate</td>
<td>67.5</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Brush height</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Minimum required distance from the soil</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>“Wasted” length</td>
<td>677.5</td>
<td>( W = A+B+C+D+E+F )</td>
</tr>
</tbody>
</table>

### Table 7 - Case 1: Envelope driven

<table>
<thead>
<tr>
<th>Distance</th>
<th>Description</th>
<th>Value [mm]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Vertical envelope</td>
<td>2300</td>
<td>Input</td>
</tr>
<tr>
<td>L</td>
<td>Rod length (inclusive of sampling tool)</td>
<td>1970</td>
<td>( L = X-A-B )</td>
</tr>
<tr>
<td>Y</td>
<td>Drilling depth</td>
<td>1622.5</td>
<td>( Y = L-C-D-E-F )</td>
</tr>
<tr>
<td>S</td>
<td>Drill translation needed stroke</td>
<td>1772.5</td>
<td>( S = Y+F )</td>
</tr>
</tbody>
</table>

### Table 8 - Case 2: Drilling depth driven

<table>
<thead>
<tr>
<th>Distance</th>
<th>Description</th>
<th>Value [mm]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>Drilling depth</td>
<td>2000</td>
<td>Input</td>
</tr>
<tr>
<td>L</td>
<td>Rod length (inclusive of sampling tool)</td>
<td>2347.5</td>
<td>( L = Y+F+E+D+C )</td>
</tr>
<tr>
<td>X</td>
<td>Vertical envelope</td>
<td>2677.5</td>
<td>( X = L+B+A )</td>
</tr>
<tr>
<td>S</td>
<td>Drill translation needed stroke</td>
<td>2150</td>
<td>( S = Y+F )</td>
</tr>
</tbody>
</table>

### Table 9 - CAD modeling at the moment

<table>
<thead>
<tr>
<th>Distance</th>
<th>Description</th>
<th>Value [mm]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Vertical envelope</td>
<td>2410</td>
<td>Input</td>
</tr>
<tr>
<td>L</td>
<td>Rod length (inclusive of sampling tool)</td>
<td>2080</td>
<td>( L = X-A-B )</td>
</tr>
<tr>
<td>Y</td>
<td>Drilling depth</td>
<td>1732.5</td>
<td>( Y = L-C-D-E-F )</td>
</tr>
<tr>
<td>S</td>
<td>Drill translation needed stroke</td>
<td>1882.5</td>
<td>( S = Y+F )</td>
</tr>
</tbody>
</table>
Test activity

In the frame of the running activity, two typologies of test are foreseen:

- early tests (Concept Assessment Tests) on prototypes of cutting/sampling heads (completed)
- testing at Drill Breadboard level (scheduled by 2015)

*Early tests on prototypes of cutting/sampling heads have been* performed on six different solution/sizes, some of them based on PCD diamond technology and some on carbide technology (under Argon glove box and temperatures range -150/-100°C)

Soil simulant an admixture of:
- ‘base regolith’ NU-LHT-2M
- volatile/ices entrapped in various forms (percentages of 6% and 11.9% saturated)

Example of recorded plot (it refers to 36 mm bit, solid ice, no hammer)
- Example only-
Test activity (cont)

A Drill Breadboard is designed and will be manufactured representative of the final Drill System model as far as the key aspects of:

• roto-hammer group
• length of drill string
• sampling tool

This Drill BB will be tested over strokes of 700 mm utilizing a specific test equipment in:

• lab conditions (sample material conditioned in the -165/-100 °C range under glove box
• dedicated Thermal Vacuum (T/V) chamber with the soil specimen conditioned at -180 °C

Schematics of the Drll BB installation in the large T/V chamber
Test activity (cont)

TS1 = drill tool bit (L-GRASP)
TS2 = sampling chamber (L-GRASP)
TS3 = hammer actuator hotspot
TS4 = rotation motor
TS5 = force/torque sensor (MGSE)
TS6 = translation motor (MGSE)
Concept Assessment Tests: example (Tool 36mm – bits -15°)
Concept Assessment Tests: example (Tool 36mm – bits -15°)

\[ P_m = (C \cdot \omega + F \cdot v + f \cdot J \cdot K) \]
# Concept Assessment Tests: some results

## Force / Torque

<table>
<thead>
<tr>
<th>Water content</th>
<th>Tool size</th>
<th>Bit angle</th>
<th>Φ36 mm</th>
<th>Φ26 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Φ36 mm</td>
<td>0°</td>
<td>-15°</td>
<td>0°</td>
</tr>
<tr>
<td>5.9%</td>
<td>Force RMS [N]</td>
<td>215</td>
<td>48</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Torque RMS [Nm]</td>
<td>1.76</td>
<td>0.5</td>
<td>0.34</td>
</tr>
<tr>
<td>11.9%</td>
<td>Force RMS [N]</td>
<td>246</td>
<td>241</td>
<td>209</td>
</tr>
<tr>
<td></td>
<td>Torque RMS [Nm]</td>
<td>2.94</td>
<td>2.62</td>
<td>0.72</td>
</tr>
</tbody>
</table>

## Mechanical power: \( P_m = (C \cdot \omega + F \cdot v + f \cdot J \cdot K) \)

<table>
<thead>
<tr>
<th>Water content</th>
<th>Nexus Φ36</th>
<th>Nexus Φ26</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
<td>-15°</td>
</tr>
<tr>
<td>5.9%</td>
<td>9.5 W</td>
<td>2.9 W</td>
</tr>
<tr>
<td>11.9%</td>
<td>17.5 W</td>
<td>15.5 W</td>
</tr>
</tbody>
</table>

- Average advancing (vertical) speed = 5 mm/min
Concept Assessment Tests: hammer influence

Embedded hammer actuator (in string built) from previous program development was tested:

- Low frequency mechanical actuator (1 Hz)
- Low energy involved (0.5 J)
Concept Assessment Tests (unofficial): pure ice at -160° C

- Drill tool: D=36 mm, Beta=0°, Carbide, Coated (ice-rejection)
- Specimen: water Ice conditioned at -160° C
- Coating: CRC TEFLUB Spray (three subsequent applications separated by 10 minutes)

Initial water filling (-9% in volume for expansion accommodation)

Icy specimen
Concept Assessment Tests (unofficial): pure ice at -160° C

- Specimen temperature during test: from -160 to -100° C
- Speed range: 5, 7.5 and 10 mm/min
- Drill depth: 150+20 mm
- Max thrust level: 600 N
- Max torque level: 5.5 Nm

Thrust profile (unfiltered @ 200 Hz)  Torque profile (unfiltered @ 200 Hz)  Depth profile (+ 20mm) - schematics
Energy exchange model

Data from Concept Assessment Test is used to:

- Validate and calibrate the energy exchange model under development at Politecnico di Milano
- Estimate the temperature increase on the sample material due to heat dissipation
Conclusions

Three specific activities are being presently developed for Moon low latitude scenario at Selex-ES on behalf of ESTEC

The outcomes will encompass:

- Drill System plus Sampling Tools Breadboards specifically tested in representative conditions (up to saturated icy regolith)

- detailed Icy Sample Handling chain analysis with special attention to sample integrity and preservation

The outcomes of such activities will certainly support a deeper insight on the problematics related to drilling and sampling in the Moon South Pole hostile environment
THANK YOU FOR YOUR ATTENTION

M. Savoia

Address or e-mail reference