ARA Hot Water Drill Design and Performance

ARA Review @ NSF
Feb 20-21, 2013
Terry Benson, UW-PSL
ARA Hole Requirements

- Dry hole
- $\Phi6''$, minimum
- 200m usable depth
- 2 holes/day (achievable with 2 shifts/day)
- Straight
- Remote from S. Pole Station
ARAHWD History

2010-2011

- Initial build season
- IceCube Enhanced Hot Water Trencher -> ARAHWD
ARAHWL History

2010-2011

- Initial build season
- IceCube Enhanced Hot Water Trencher -> ARAHWL
- 5 holes @ ARA Test Bed (40m dry)
- 1 test hole (180m wet)
- Drill under-powered
ARAHW History

2011-2012

- Modest upgrade season: +2 heaters, +recovery water pump, new melter
- First attempt to 200m, first attempt at dry holes
- 2 test holes @ ICL (190m wet, 70m dry)
- 6 instrument holes @ ARA1 (2x 60m, 4x 100m)
- Tough drilling season, equipment failures/loss, long shifts
- Lessons learned
  - Hole freeze-back faster than predicted, drilling efficiencies lower than predicted
  - Equipment not reliable
  - System not capable of producing 200m dry holes in reasonable time
  - Clear that ARA37 drill concept needed to be realized
ARAHWD History

2012-2013

- **SUCCESS!**
- Major upgrade season: new system architecture, drill/pump simultaneous, new hose reel, new drillheads, +drill control center, new generators
- 13 holes
  - All φ6+" dia x 200m deep dry
  - 1x ICL test hole
  - 6x @ ARA2
  - 6x @ ARA3
- Lessons Learned
  - It works! But new territory for drilling method and hole type
  - New equipment, some kinks to iron out
  - Operations, new system = a few growing pains
<table>
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<th>11-12 System</th>
<th>TARGET 12-13 System</th>
<th>ACTUAL 12-13 System</th>
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<td>Drilling Method</td>
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<td>100% / 0%</td>
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<td>120 m</td>
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<td></td>
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<td>1 hr</td>
<td></td>
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<td>2 hr</td>
<td></td>
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<td>to 200 meters (incl firn)</td>
<td>17 hr</td>
<td>5 hr</td>
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1. Includes total hole-to-hole cycle (setup, drill/pump, pack-up, move).
2. Time spent drilling firn and ice only.
System Schematic (deep drill configuration)

System Specs
Water recovery, drill and pump simultaneously
12 gpm drill, 6 gpm recirc
750 gal water surplus
6" x 40m firm hole in <1 hr
6" x 200m dry deep hole in 5 hr
Total hole cycle time 10 hr
Total AN8 per hole 90 gal
Total gasoline per hole 8 gal

Deep Drilling
2012 Drill System Upgrades

New Drilling Method:
PUMP/DRILL AT SAME TIME

Recirculated water column travels down with drillhead. Hot water sprays out nozzle and travels some distance back up the hole to the pump, where the water is pumped back to the surface. Hole diameter is developed between nozzle and pump.

- Closes loop and returns water during drilling
  - No snow melting, net water production
  - System capacity effectively doubled
- Leaves dry hole above
  - No freezeback!
  - 1 step = faster production rate
2012 Drill System Upgrades

PUMP/DRILL AT SAME TIME

NEW DRILLHEADS
– pump, head sensors, diameter qualifier integrated together
– nozzle stem 10m below
– motor controller for auto run

NEW HOSE/CABLE BUNDLE
– 2 hoses (supply/return, 1” ID, load-carrying)
– combo cable (3-phase pump power and signal cable)

NEW HOSE REEL
– single width spiral configuration
– dual-motor drum+sheave load sharing
– no level wind for simplicity and improved safety
– insulated
2012 Drill System Upgrades

NEW DRILL CONTROL CENTER (DCC)
- centralized control and monitor
- heated DNF space for motor drives and controls
- more reliable safeties and controls

NEW GENERATORS
- 2x (redundant) ASC-supplied 50 kW generators
- high reliability

INSTRUMENTATION AND ELECTRICAL
- additional system instrumentation
- reworked electrical distribution
2012 Drill System Upgrades

IMPROVED PLUMBING AND HEATING
- New charge pump
- Simplified plumbing, flexibility, bigger lines
- Tested/tuned heaters

SHELTERING
- Warm space and wind breaks for crew and equipment
- NGH

WIRELESS DAQ
- Drill data recorded to laptop
- PDAs
Other things that made success possible

- Contributions of the Collaboration and partners
  - Delaware: James Roth electrical lead, full time on/off ice
  - Belgium: Thomas Meures 2nd season as driller, 2 weeks of help off-ice in North
  - Kansas: Rob Young transitioned to full time driller mid-season
  - ASC: Bert transitioned to full time driller mid-season (good model for future seasons)

- Experienced and well-rounded crew

- Fantastic support from ASC
  - Cargo
    - Real-time support requests (Hose reel in heavy shop, meals)

- Great weather!

- Thorough test phase in the North prior to shipment

- Thorough system shakedown at ICL prior to moving into field

- Well prepared/maintained documentation, procedures, and logging
### Flow X Temp

<table>
<thead>
<tr>
<th>Flow [gpm]</th>
<th>50°C</th>
<th>60°C</th>
<th>70°C</th>
<th>80°C</th>
<th>85°C</th>
<th>90°C</th>
<th>Slug Delay [min]</th>
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<tbody>
<tr>
<td>6</td>
<td>300</td>
<td>360</td>
<td>420</td>
<td>480</td>
<td>510</td>
<td>540</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>400</td>
<td>480</td>
<td>560</td>
<td>640</td>
<td>680</td>
<td>720</td>
<td>5.0</td>
</tr>
<tr>
<td>10</td>
<td>500</td>
<td>600</td>
<td>700</td>
<td>800</td>
<td>850</td>
<td>900</td>
<td>3.8</td>
</tr>
<tr>
<td>12</td>
<td>600</td>
<td>720</td>
<td>840</td>
<td>960</td>
<td><strong>1020</strong></td>
<td>1080</td>
<td>3.0</td>
</tr>
<tr>
<td>14</td>
<td>700</td>
<td>840</td>
<td>980</td>
<td>1120</td>
<td>1190</td>
<td>1260</td>
<td>2.1</td>
</tr>
<tr>
<td>16</td>
<td>800</td>
<td>960</td>
<td>1120</td>
<td>1280</td>
<td>1360</td>
<td>1440</td>
<td>1.9</td>
</tr>
</tbody>
</table>

### Drill Speed [m/min], 7.5" Hole

<table>
<thead>
<tr>
<th>Flow X Temp [gpm x °C]</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
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<tbody>
<tr>
<td>300</td>
<td>0.21</td>
<td>0.19</td>
<td>0.17</td>
<td>0.16</td>
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<tr>
<td>400</td>
<td>0.28</td>
<td>0.25</td>
<td>0.23</td>
<td>0.21</td>
</tr>
<tr>
<td>500</td>
<td>0.35</td>
<td>0.32</td>
<td>0.29</td>
<td>0.26</td>
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<tr>
<td>600</td>
<td>0.42</td>
<td>0.38</td>
<td>0.35</td>
<td>0.31</td>
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<tr>
<td>700</td>
<td>0.49</td>
<td>0.45</td>
<td>0.40</td>
<td>0.37</td>
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<tr>
<td>800</td>
<td>0.56</td>
<td>0.51</td>
<td>0.46</td>
<td>0.42</td>
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<tr>
<td>900</td>
<td>0.63</td>
<td>0.57</td>
<td>0.52</td>
<td>0.47</td>
</tr>
<tr>
<td>1000</td>
<td>0.70</td>
<td>0.64</td>
<td>0.58</td>
<td>0.52</td>
</tr>
<tr>
<td>1100</td>
<td>0.77</td>
<td>0.70</td>
<td>0.64</td>
<td>0.58</td>
</tr>
<tr>
<td>1200</td>
<td>0.84</td>
<td>0.76</td>
<td>0.69</td>
<td>0.63</td>
</tr>
<tr>
<td>1300</td>
<td>0.91</td>
<td>0.83</td>
<td>0.75</td>
<td>0.68</td>
</tr>
</tbody>
</table>

(Example of drill tools available to crew)
ARA Drill Roadmap
Rev 12.30.12

Diameter estimation, assuming constant pump head and drill rate:
\[ D=2.849\sqrt{\left(\frac{\text{Return Flow} - \text{Supply Flow}}{\text{Drill Rate}}\right)} \]

Dia in inches
Flows in GPM
Drill rate in m/min

(Example of drill tools available to crew)
This shows there were no serious system issues that prevented us from following our prescribed drill strategy. Most holes looked like this.
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6 holes in 9 working days
6 holes in 7 working days

ARAHWD 12-13
Drilling Timeline

... ICL

ARA 2

ARA 3

6 holes in 9 working days
6 holes in 7 working days

... ICL

ARA 2

ARA 3

6 holes in 9 working days
6 holes in 7 working days
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Review
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ARAHWDD 12-13
Depth vs Time Overlay, Aligned at 200m Depth, Deep Drilling Only (no Firn)

Notes:
Test Hole - Backtracked at 140m to tune hose load sharing parameters
A2D3 - Difficult getting through narrow spot at 27m
A3D1 - Difficult getting the deep drill stem through the firn hole

A2D6, A3D3, A3D6 omitted for clarity; these holes either have insufficient data, timeouts, or involved multiple drilling attempts
### 12-13 Hole Summary Chart

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>1</td>
<td>Test Hole</td>
<td>ICL</td>
<td>1.4</td>
<td>7.0</td>
<td>8.4</td>
<td>Backtrack @ 140m to tune torque parameters</td>
<td>91</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>A2D1</td>
<td>ARA2</td>
<td>1.5</td>
<td>5.2</td>
<td>6.9</td>
<td></td>
<td>74</td>
<td>5</td>
<td>131</td>
</tr>
<tr>
<td>3</td>
<td>A2D2</td>
<td>ARA2</td>
<td>1.1</td>
<td>6.7</td>
<td>7.9</td>
<td></td>
<td>85</td>
<td>8</td>
<td>795</td>
</tr>
<tr>
<td>4</td>
<td>A2D5</td>
<td>ARA2</td>
<td>NA</td>
<td>7.4</td>
<td>NA</td>
<td></td>
<td>86</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>A2D4</td>
<td>ARA2</td>
<td>1.3</td>
<td>5.4</td>
<td>6.9</td>
<td>good hole, good data, switch to other drillhead</td>
<td>74</td>
<td>5</td>
<td>836</td>
</tr>
<tr>
<td>6</td>
<td>A2D3</td>
<td>ARA2</td>
<td>1.3</td>
<td>7.7</td>
<td>9.0</td>
<td>Difficult getting past narrow spot @ 27m</td>
<td>98</td>
<td>8</td>
<td>51</td>
</tr>
<tr>
<td>7</td>
<td>A2D6</td>
<td>ARA2</td>
<td>1.1</td>
<td>11.8</td>
<td>12.9</td>
<td>12/18 Firma + Partial, 12/20 Deep but water fill in (136m) and head sensor fail, final depth delivered 12/23</td>
<td>139</td>
<td>10</td>
<td>956</td>
</tr>
<tr>
<td>8</td>
<td>A3D4</td>
<td>ARA3</td>
<td>1.5</td>
<td>5.8</td>
<td>7.3</td>
<td>Good hole</td>
<td>79</td>
<td>4</td>
<td>1468 (?)</td>
</tr>
<tr>
<td>9</td>
<td>A3D1</td>
<td>ARA3</td>
<td>1.4</td>
<td>7.2</td>
<td>8.7</td>
<td>Difficult getting nozzle stem through firma hole</td>
<td>93</td>
<td>7</td>
<td>829</td>
</tr>
<tr>
<td>10</td>
<td>A3D3</td>
<td>ARA3</td>
<td>3.1</td>
<td>6.4</td>
<td>9.4</td>
<td></td>
<td>102</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>A3D2</td>
<td>ARA3</td>
<td>2.2</td>
<td>4.8</td>
<td>7.0</td>
<td></td>
<td>76</td>
<td>6</td>
<td>588</td>
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<tr>
<td>12</td>
<td>A3D5</td>
<td>ARA3</td>
<td>1.8</td>
<td>5.7</td>
<td>7.4</td>
<td></td>
<td>80</td>
<td>6</td>
<td>1058</td>
</tr>
<tr>
<td>13</td>
<td>A3D6</td>
<td>ARA3</td>
<td>2.1</td>
<td>5.6</td>
<td>7.8</td>
<td></td>
<td>84</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td><strong>BEST</strong></td>
<td></td>
<td></td>
<td><strong>1.1</strong></td>
<td><strong>4.8</strong></td>
<td><strong>6.9</strong></td>
<td></td>
<td><strong>74</strong></td>
<td><strong>4</strong></td>
<td><strong>1058</strong></td>
</tr>
<tr>
<td><strong>WORST</strong></td>
<td></td>
<td></td>
<td><strong>3.1</strong></td>
<td><strong>11.8</strong></td>
<td><strong>12.9</strong></td>
<td></td>
<td><strong>139</strong></td>
<td><strong>10</strong></td>
<td><strong>51</strong></td>
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<tr>
<td><strong>AVERAGE</strong></td>
<td></td>
<td></td>
<td><strong>1.6</strong></td>
<td><strong>6.7</strong></td>
<td><strong>8.3</strong></td>
<td></td>
<td><strong>89</strong></td>
<td><strong>7</strong></td>
<td><strong>746</strong></td>
</tr>
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A: Fuel estimates based on (duration)x(fuel rate)
Gen rate = 2.05 gph
Heater rate = 8.75 gph
### 11-12 System vs. 12-13 System

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<td>+600 gal</td>
<td>+355 gal average  +504 gal best?</td>
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<td>1.9 hr</td>
<td>1 hr</td>
<td>1.6 hr average  1.1 hr best</td>
</tr>
<tr>
<td>to 100 meters (incl firn)</td>
<td>4.2 hr</td>
<td>2 hr</td>
<td>4.0 hr average est. 2.8 hr best est.</td>
</tr>
<tr>
<td>to 200 meters (incl firn)</td>
<td>17 hr</td>
<td>5 hr</td>
<td>8.3 hr average  5.9 hr best of the best</td>
</tr>
</tbody>
</table>

1. Includes total hole-to-hole cycle (setup, drill/pump, pack-up, move).
2. Time spent drilling firn and ice only.
Operations

- No injuries
- A few bouts of sickness, morale overall high
- 5 core drillers + 1-2 helpers
  - 4-5 drillers needed at start/end of hole
  - 2-3 drillers needed during drilling
- Arrival/Departure checklists were utilized, manual drill logs in addition to DAQ, pre-op meetings
- Most shifts during production drilling extended to 12 hrs
  - Unsustainable for extended seasons
  - However, some steps (pickling, warm-up, maintenance) eliminated with two-shift operation, and operations expected to become more efficient (new system)
  - We believe this system can produce 2 holes per day with shift limited to 10 hours or less
Hole Quality

FIRN
0-40m
Oversized, ragged, offshoots

TRANSITION ZONE
40-120m
Frosty, post-drill ice structures

DEEP ICE
120-200m
Smooth and uniform
Questions?
Additional Slides...
ARA Drillhead Overview

- Hot circulation ring around top edge of drillhead for emergency up-reaming
- Top section houses manifolding, pressure transducers, and recirculation valving
- 4x insulated SS tubes carry the hot water around the pump
- Pump
- Pump Inlet
- Motor
- Polycarbonate shroud directs return water over motor surface to provide cooling
- Cold Return water enters pump shroud here. During backflush, water exits here and pours over qualifier
- Compliant hole diameter qualifier provides indication of narrow spots and maximizes return water velocity
- Hot Supply water exits here, attach firn nozzle or extension hose

FIRN Drilling
- Firn Nozzle Attachment
- Full Cone Spray
- Extension Hose L = 10m
- Nozzle Stem (weight)
- Jet Spray

DEEP Drilling
- 4x sets of tie rods support load below the pump
**ARA Hose Reel Overview**

**Hose and cable bundle**
- 2x hoses and 1x combo cable
- Multi-reel joined at hole not a solution
  - Load to be shared amongst all 3 members, intricate syncing control would be required
  - Extra task at hole of joining/separating members
- Manufactured umbilical with round cross-section too expensive, too big
- Decided to build custom from separate pieces, resulting in a ribbon profile

**Single width spiral configuration**
- Accommodates hose bundle design with ribbon cross-section
- Improves safety and reduces complexity by eliminating level wind and associated fleet distance
- 2x familiar applications that have successfully utilized this design
  - Rapid Air Movement (RAM) Drill
  - Independent Fnr Drill
- Large diameter required to accommodate full length of hose, so design incorporates a 45° pivot to allow the reel to fit on an LC-130 aircraft

**Dual-drive, load sharing system**
- A dry hole results in high down-hole loads (no buoyancy)
- High loads + many layers would collapse the lower layers of hose if using only the drum to react the load
- Motorized sheave utilizes friction with the bundle to react a majority (~80%) of the down-hole load, like a capstan winch
- In this mode, the sheave operates in velocity mode and is master to the drum, therefore payout and speed is directly controlled without effects of changing diameter
- The drum operates in torque mode and is slave to the sheave, and the hose is wrapped onto the drum at only 20% down-hole load

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**Diagram:**
- Structural Insulated Panels (SIPs) used for flanges
- Motorized sheave operates in speed mode during deep drilling, is master to drum
- Mounting face for beam and trolley hoist
- Redundant load cells
- Payout/speed encoder
- Other Side:
  - 2-port rotary hydraulic union
  - Failsafe disc brake
  - Heated valving box
- Electrical slip ring (480v 3ph, comms)
- Drum operates in torque mode during deep drilling, is slave to sheave
- Skis allow for light towing on snow

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**SHIP**
Position

**INSTALLED**
Position
ARA 12-13 Fuel (AN8) by Phase
Includes all AN8 fuel usage (drilling, heat, vehicles)
Amounts in gallons

Idle Btw Holes
1210
39%

Startup
750
24%

Drilling
1162
37%

Total Season Fuel
3122 gal AN8
90 gal Gasoline*

*Gasoline amount does not include vehicle nor snowmobile usage
Water Usage/Production

A2D4 - Water Gain and Tank Level

Net Water Gain [gal]

-1500.00
-1000.00
-500.00
0.00
500.00
1000.00
1500.00
2000.00

Elapsed Time [hr]

0.00
2.00
4.00
6.00
8.00

Water Tank Level [m]

0.5
0.7
0.9
1.1
1.3
1.5
1.7

Net Water Gain

Water Tank Level
Why Hot Water?

• Leverage experience and equipment available towards end of IceCube drilling
• Fast
• Other technologies considered
  – Rapid Air Movement (RAM) drill
    • Air compressors supply a high speed air motor at end of drill hose, spinning a cutting bit. Chips are carried out of hole by return air flow.
    • Very fast, φ4” dia x 90m in 20 min in some field locations
    • Would require basically new drill to accommodate φ6” dia x 200m holes
    • Firn at South Pole very deep = too much return air escapes = chips not carried out of hole
    • Existing drill tested at South Pole during 10-11 season, average depth achieved was about 40m
  – Reverse Circulating Drill Rig
    • Discussed with manufacturers, an existing suitable rig was identified, but would require some rework for our application
    • Initial field testing of this technology too expensive and risky, would need to invest $700K+ for first field season, with too many unknowns
    • Needed to choose primary path (hot water) and focus on that, so this concept is young, but minimal efforts have been continued in parallel
Modeling

- Performance models
  - EES model revised since 11-12 to reflect new system architecture and better-understood system efficiencies
  - Excel model done independently and in parallel
  - The two models were used to validate each other
- Hole refreeze
  - IceCube thermal model tailored for ARA to predict refreeze rate and help strategize water-filled holes (done in early 11-12 season)
- Nozzle distance
  - IceCube thermal model used to help determine target distance between nozzle and pump. This is new territory for the thermal model. ARA 12-13 drill data will be used to validate and hone some of the principle assumptions made in the thermal model in the nozzle region.
ARA 3 Station Detail
Rev 01-15-13

MAGNETIC NORTH
GRID NORTH
PREVAILING WIND

WT 3 CABLE (2696m)

CENTER - 32245'-6", 51068'-4"
D1 - 32264'-4", 51094'-10"
D2 - 32218'-1", 51086'-0"
D3 - 32227'-7", 51041'-1"
D4 - 32274'-0", 51050'-9"
D5 - 32216'-9", 51196'-11"
D6 - 32117'-6", 51040'-6"

ARA 3 Detail Map