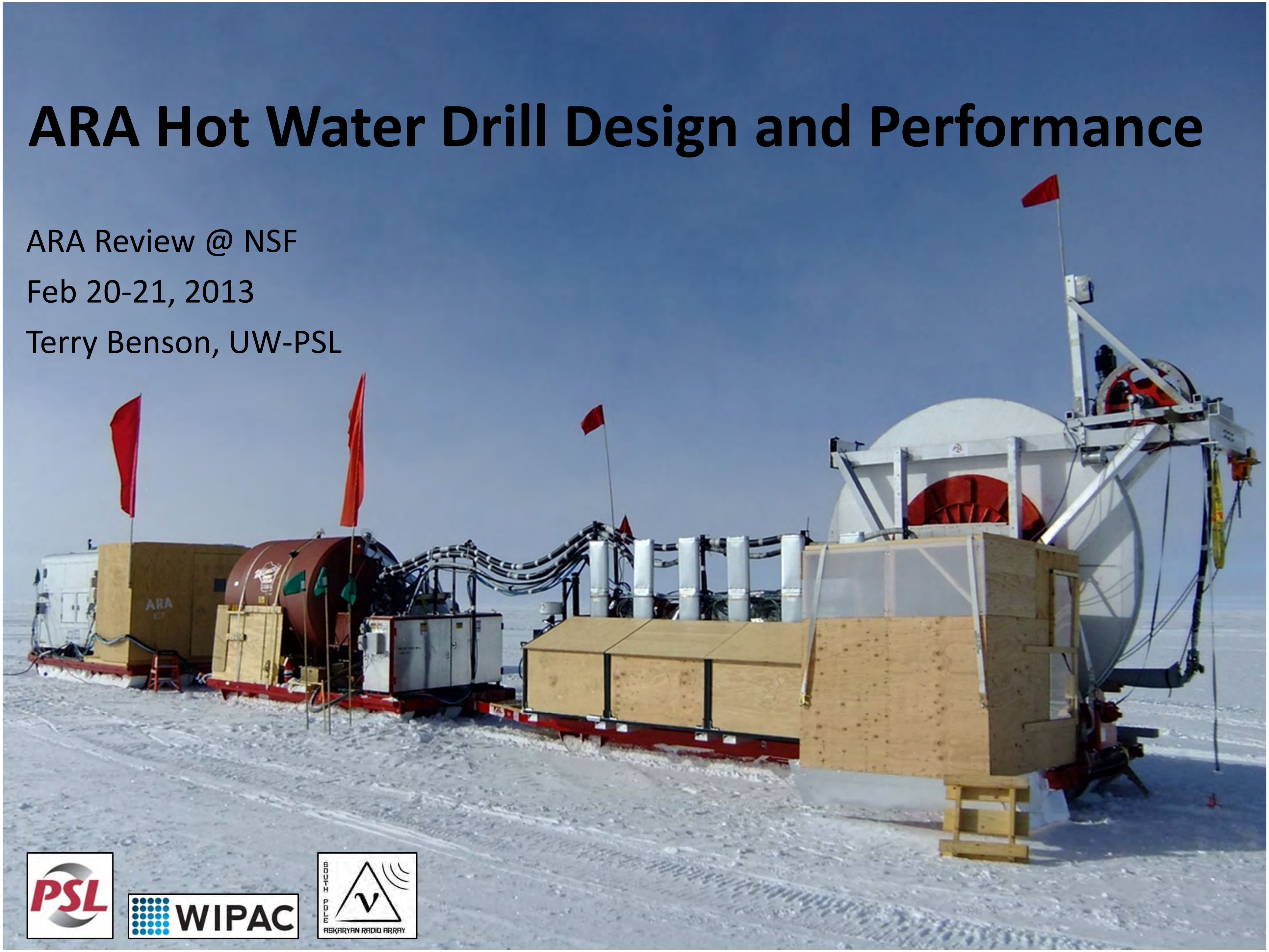
ARA Hot Water Drill Design and Performance

ARA Review @ NSF

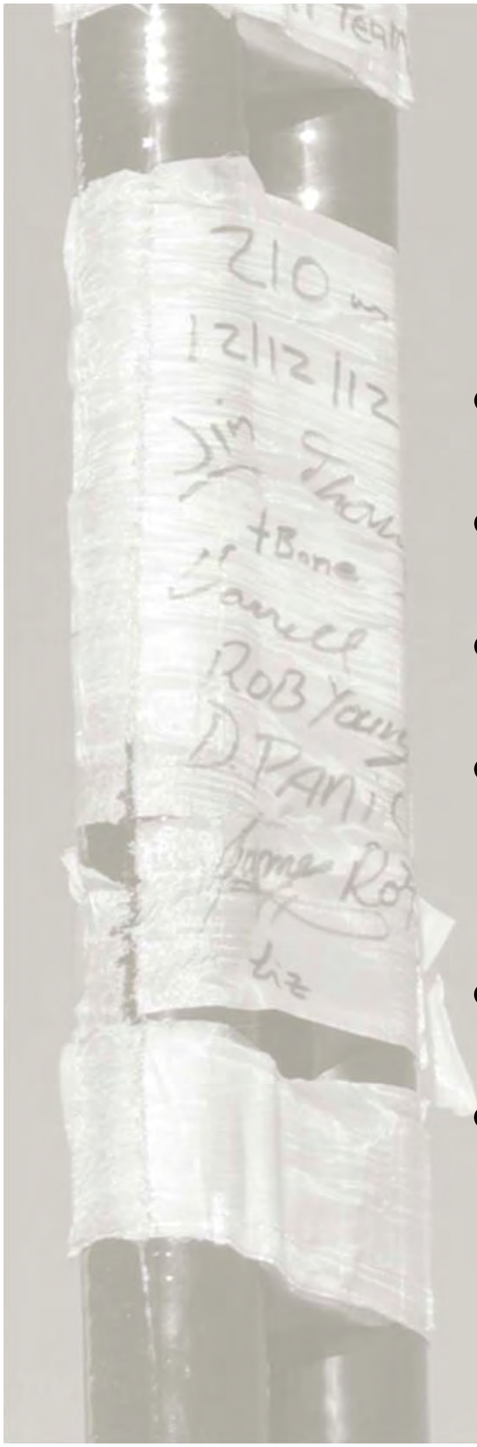
Feb 20-21, 2013

Terry Benson, UW-PSL



PSL WIPAC

SOUTH POLE ASKARYAN RADIO ARRAY



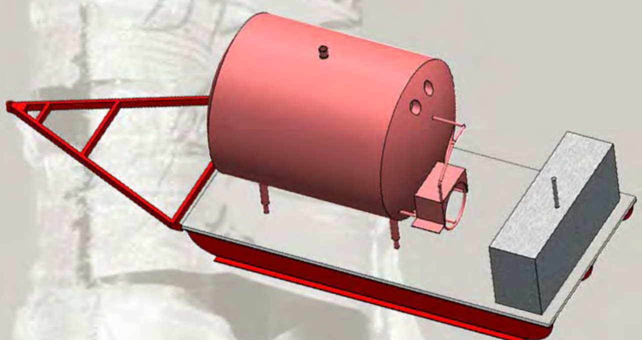
ARA Hole Requirements

- Dry hole
- Φ6”, minimum
- 200m usable depth
- 2 holes/day (achievable with 2 shifts/day)
- Straight
- Remote from S. Pole Station

ARAHWD History

2010-2011

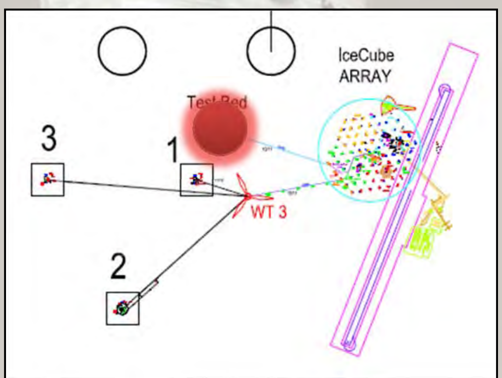
- Initial build season
- IceCube Enhanced Hot Water Trencher -> ARAHWD

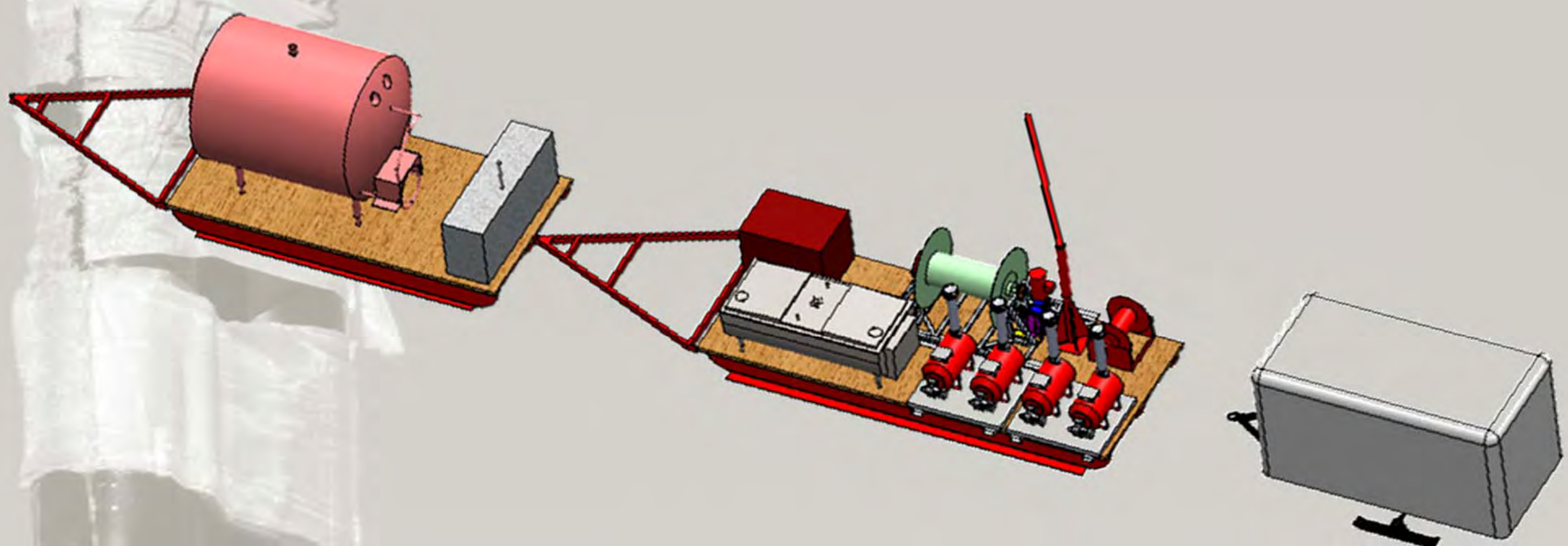


ARAHWD History

2010-2011

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

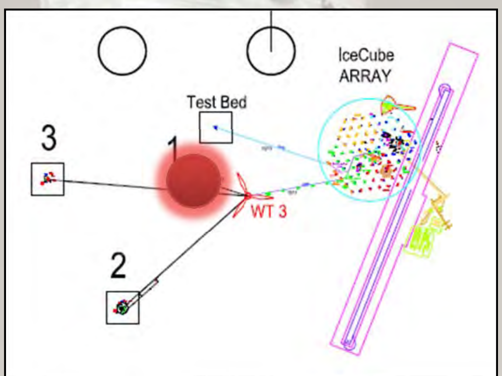


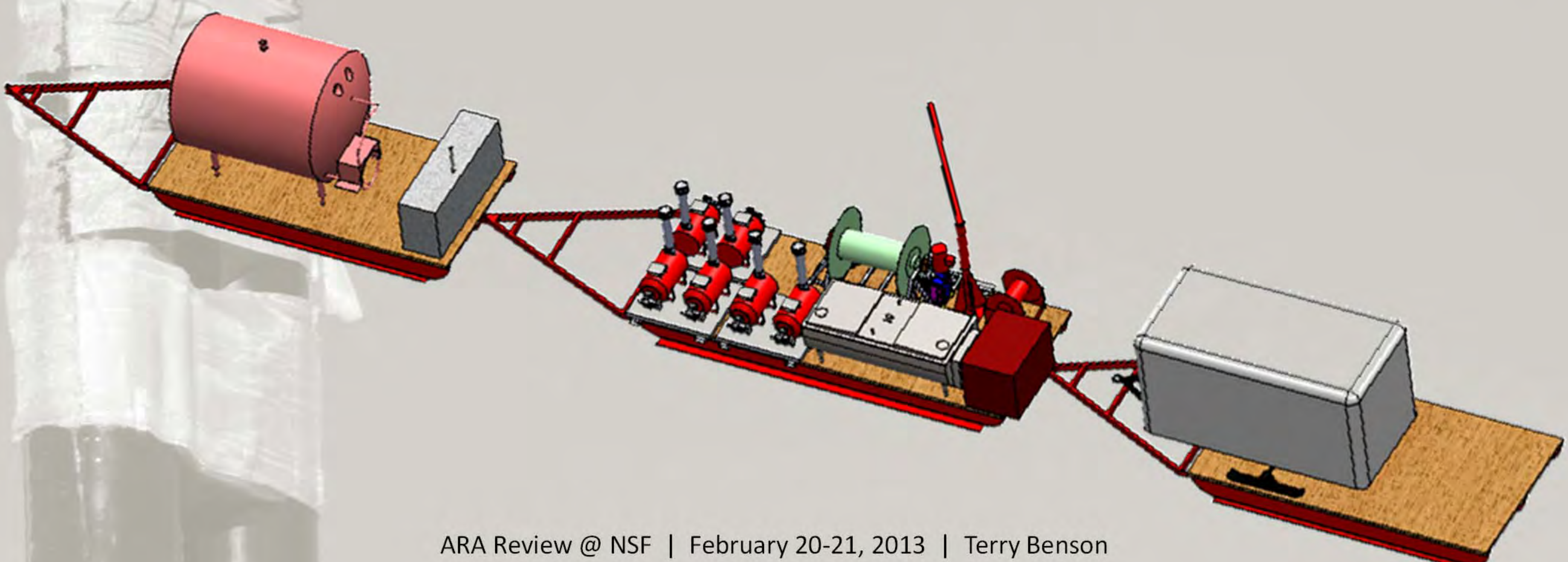


ARAHWD History

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

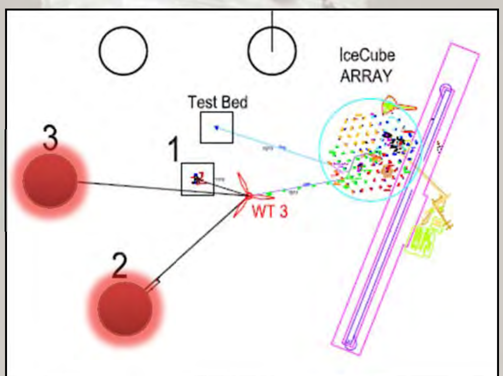


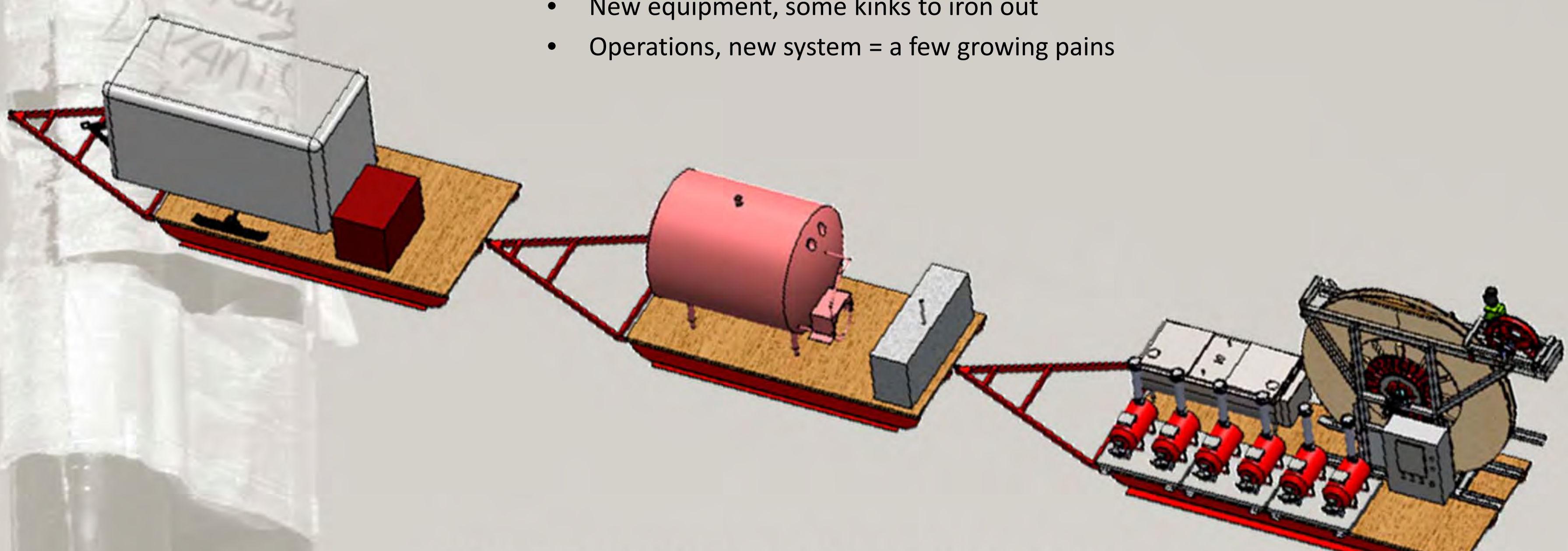


ARAHWD History

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



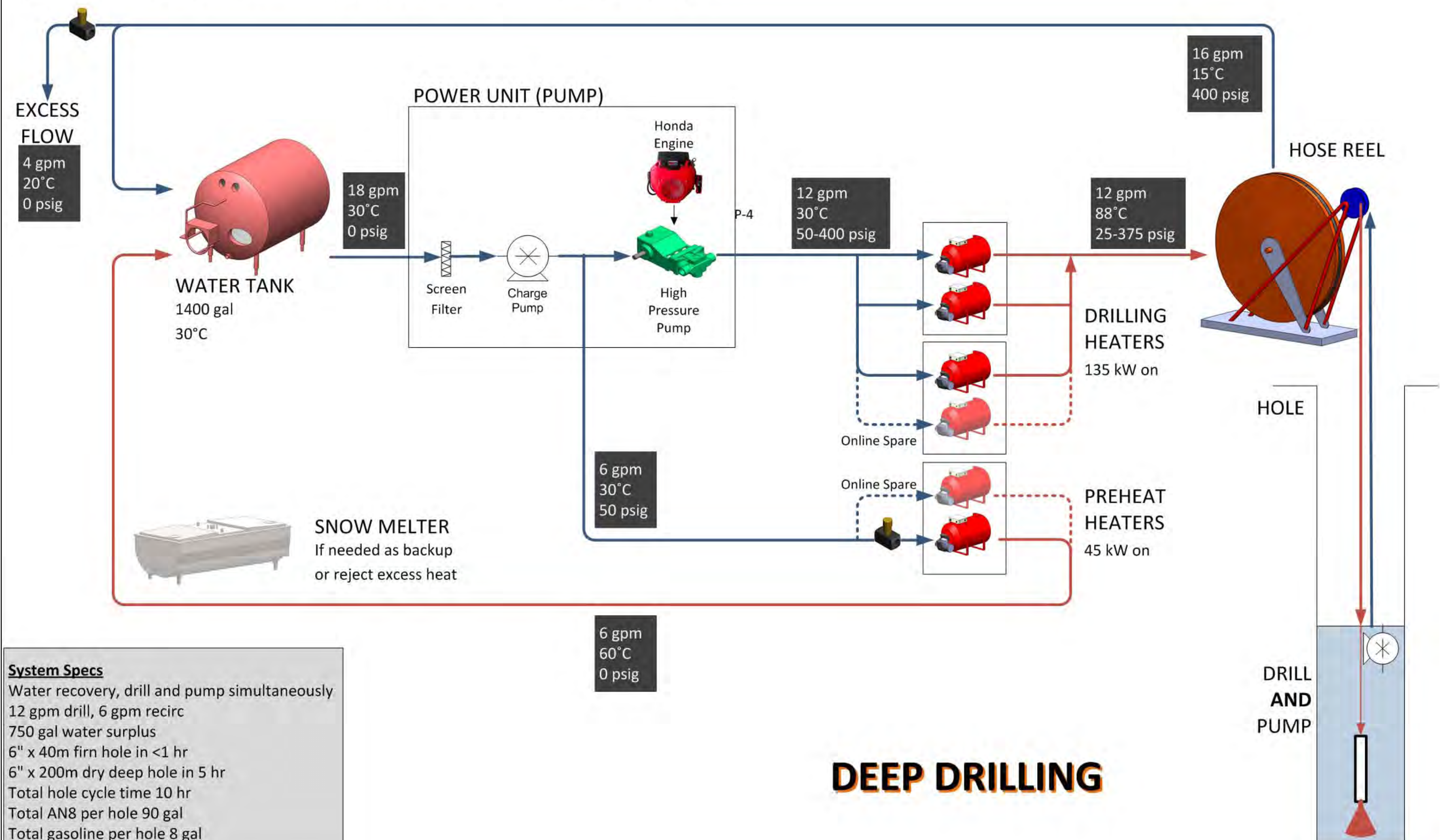


11-12 System vs. 12-13 System

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

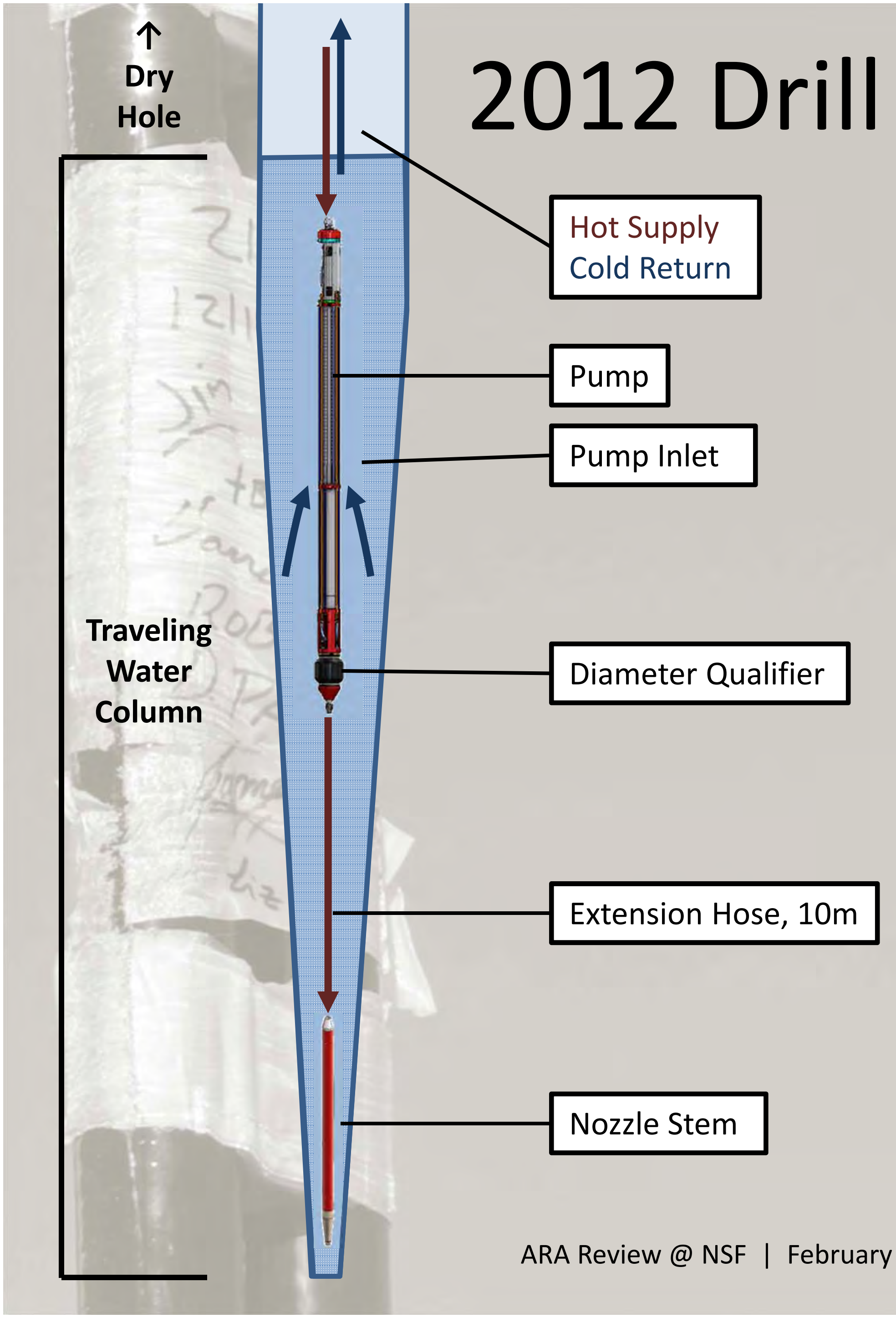
	11-12 System	TARGET 12-13 System	ACTUAL 12-13 System
Drilling Method	Lost-water drilling	Water-recovery	
Pumping Method	Drill, then pump	Drill/pump simultaneous	
Drill Water Deliver	10 GPM at 87°C	12 GPM at 88°C	
% power down-hole/snow-melting	45% / 55%	100% / 0%	
Net Water Production per 100 meters	-2500 gal	+600 gal	
Drilling Rate	0.34 m/min	0.6 – 1.0 m/min	
Max Target Depth in 10 hr[1]	120 m	200 m	
Time[2] to drill Φ6+", dry hole…			
to 40 meters (firn only)	1.9 hr	1 hr	
to 100 meters (incl firn)	4.2 hr	2 hr	
to 200 meters (incl firn)	17 hr	5 hr	

ARAHWD | System Schematic (deep drill configuration) | 2.14.13



System Specs
Water recovery, drill and pump simultaneously
12 gpm drill, 6 gpm recirc
750 gal water surplus
6" x 40m firn 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

2012 Drill System Upgrades



<u>New Drilling Method</u>:
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

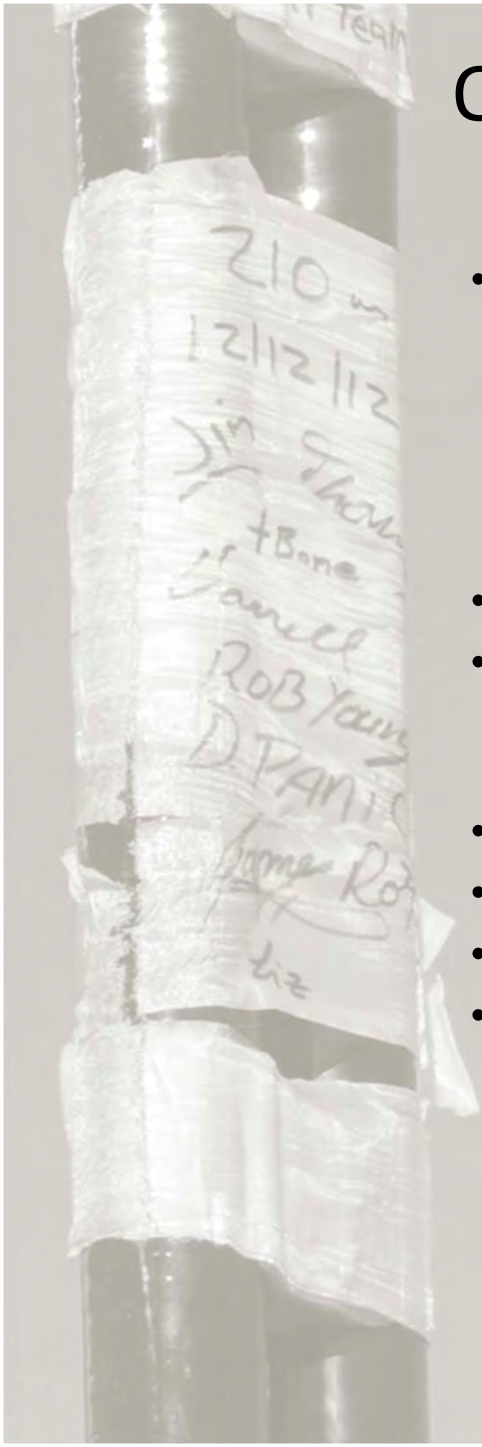
- New charge pump
- simplified plumbing, flexibility, bigger lines
- tested/tuned heaters

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

DRILL SPEED: 7.5” hole

ARAHWD
2012

Flow X Temp

Temp [C]

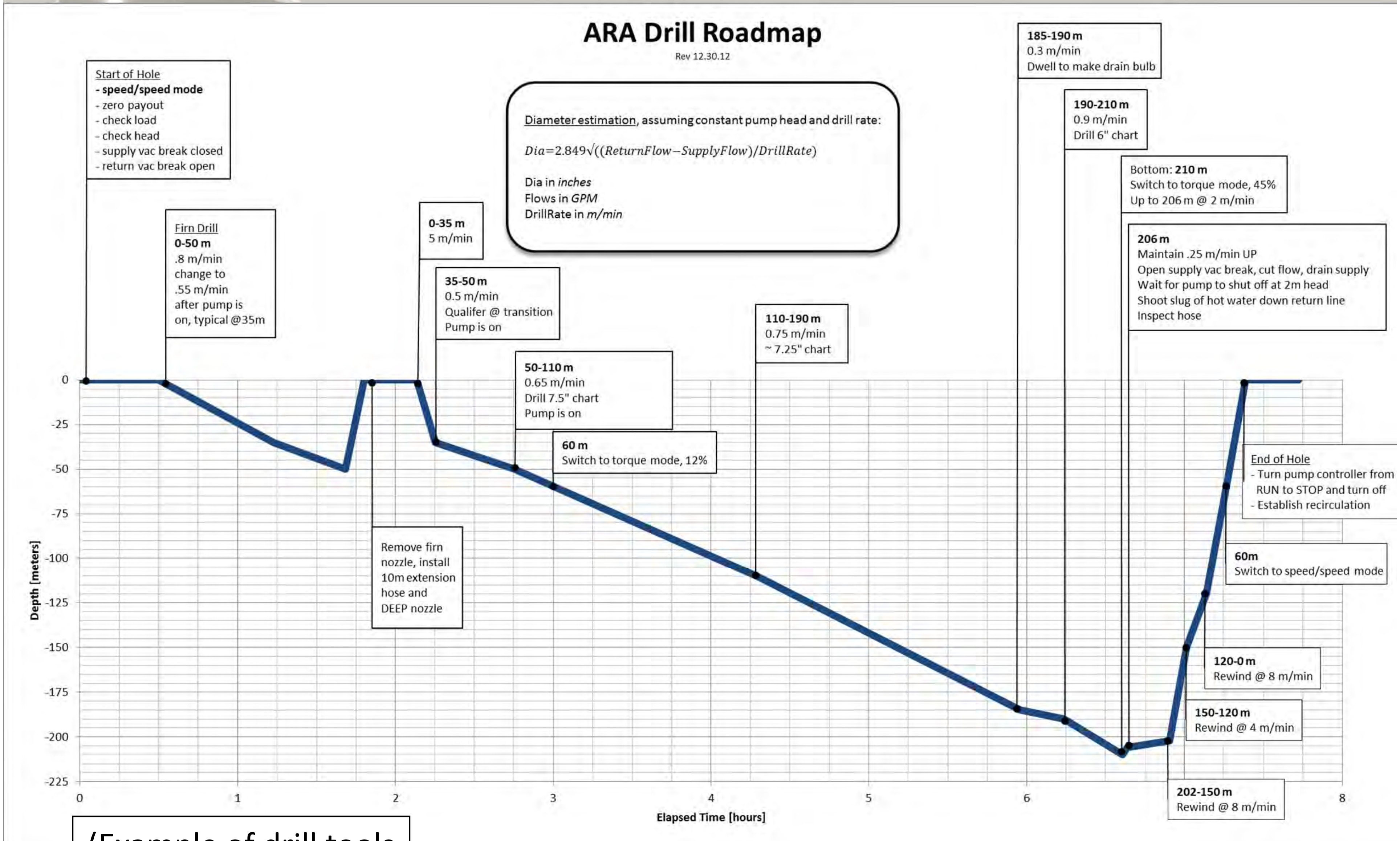
Flow [gpm]	50	60	70	80	85	90	Slug Delay [min]
6	300	360	420	480	510	540	5.0
8	400	480	560	640	680	720	3.8
10	500	600	700	800	850	900	3.0
12	600	720	840	960	**1020**	1080	2.5
14	700	840	980	1120	1190	1260	2.1
16	800	960	1120	1280	1360	1440	1.9

Drill Speed [m/min], 7.5" Hole

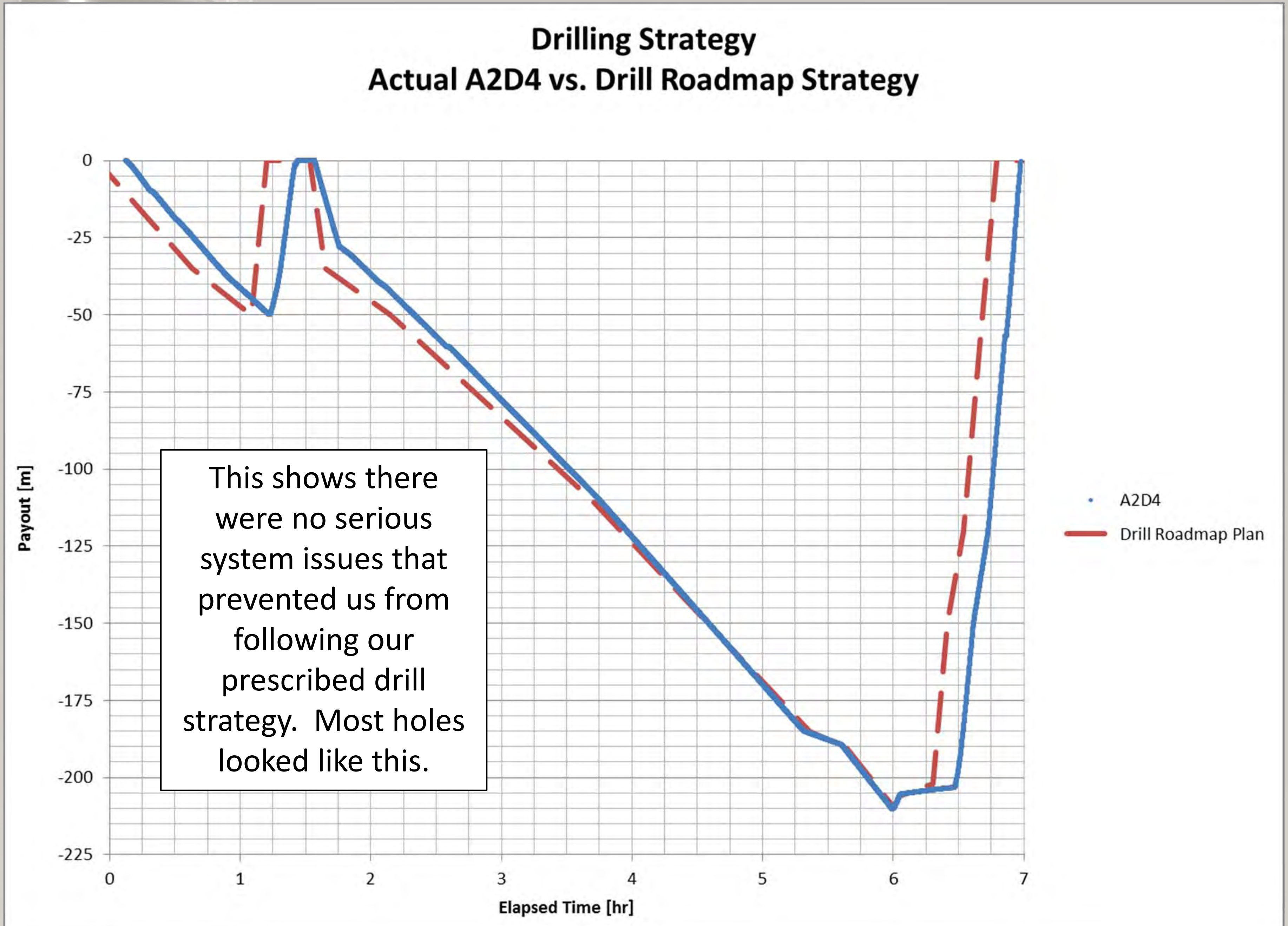
Return Water Temp [C]

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

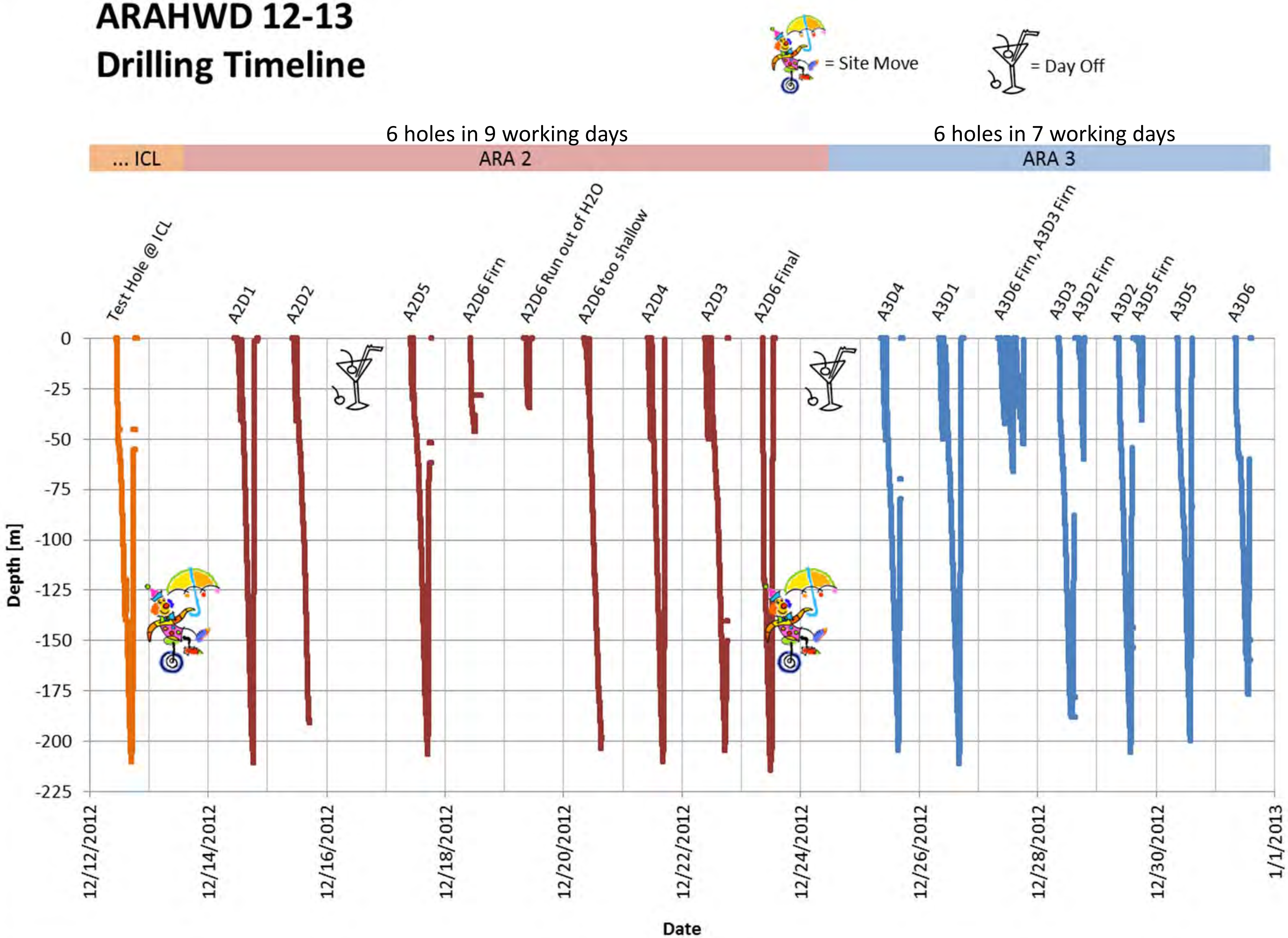
(Example of drill tools available to crew)

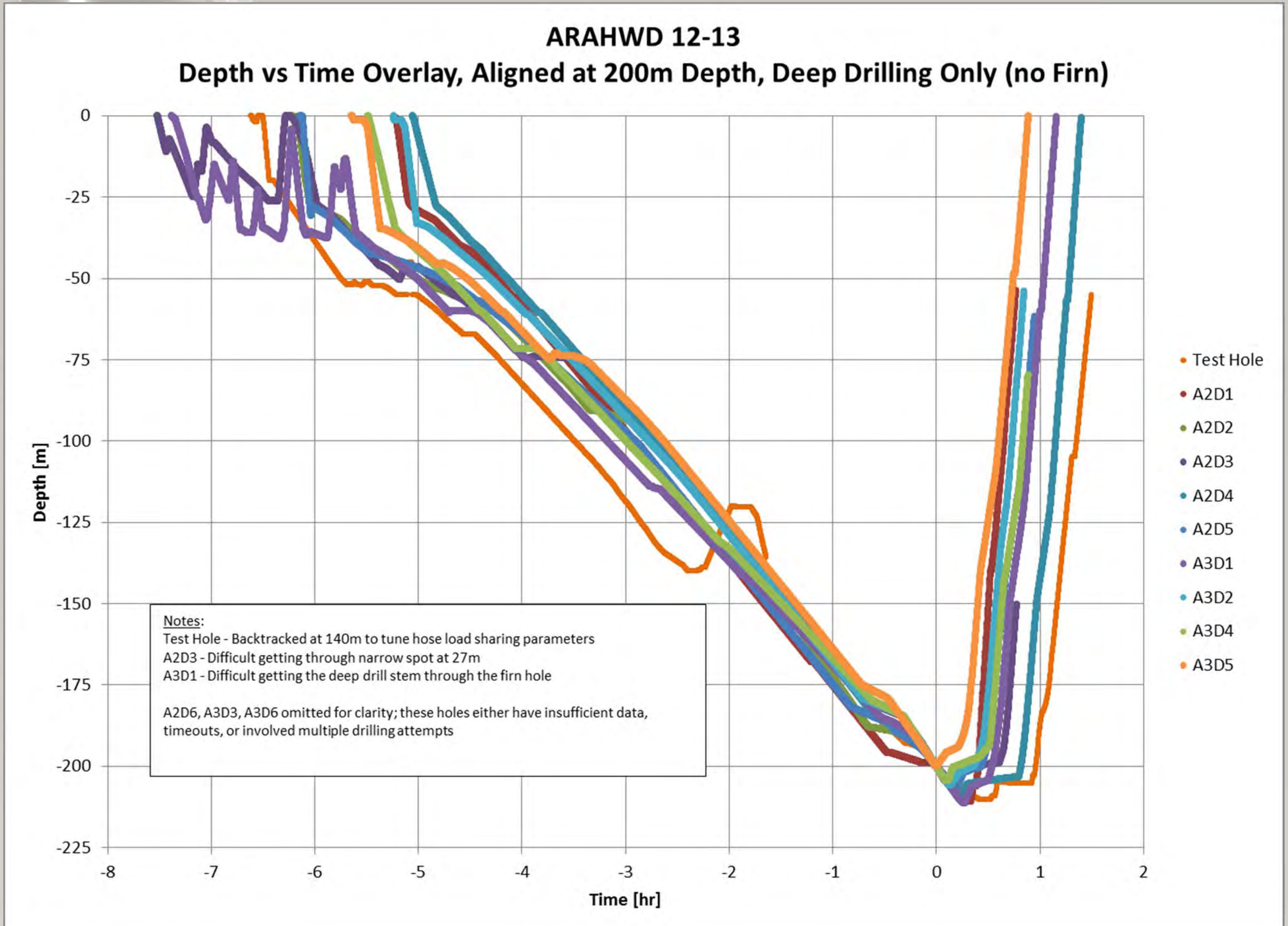


(Example of drill tools available to crew)


Drilling Strategy
Actual A2D4 vs. Drill Roadmap Strategy
0
-25
-50
-75
-100
-125
-150
-175
-200
-225
Payout [m]
0
1
2
3
4
5
6
7
Elapsed Time [hr]
A2D4
Drill Roadmap Plan
This shows there were no serious system issues that prevented us from following our prescribed drill strategy. Most holes looked like this.

ARAHWD 12-13
Drilling Timeline




ARAHWD 12-13
Depth vs Time Overlay, Aligned at 200m Depth, Deep Drilling Only (no Firn)
0
-25
-50
-75
-100
-125
-150
-175
-200
-225
Depth [m]
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
Time [hr]
Test Hole
A2D1
A2D2
A2D3
A2D4
A2D5
A3D1
A3D2
A3D4
A3D5
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

Hole Sequence	Hole	Location	Durations [hr] Firn Drill	Deep Drill	Total	Issues/Comments	Fuel AN8 [gal] [A]	Gasoline [gal]	Net Water Recovery [gal]
1	**Test Hole**	ICL	1.4	7.0	8.4	Backtrack @ 140m to tune torque parameters	91	7	-
2	**A2D1**	ARA2	1.5	5.2	**6.9**	-	**74**	5	131
3	**A2D2**	ARA2	**1.1**	6.7	7.9	-	85	8	795
4	**A2D5**	ARA2	NA	7.4	NA	-	86	9	-
5	**A2D4**	ARA2	1.3	5.4	**6.9**	good hole, good data, switch to other drillhead	**74**	5	836
6	**A2D3**	ARA2	1.3	7.7	9.0	Difficult getting past narrow spot @ 27m	98	8	**51**
7	**A2D6**	ARA2	**1.1**	**11.8**	**12.9**	12/18 Firn + Partial, 12/20 Deep but water fill in (136m) and head sensor fail, final depth delivered 12/23	**139**	**10**	956
8	**A3D4**	ARA3	1.5	5.8	7.3	Good hole	79	**4**	1468 (?)
9	**A3D1**	ARA3	1.4	7.2	8.7	Difficult getting nozzle stem through firn hole	93	7	829
10	**A3D3**	ARA3	**3.1**	6.4	9.4	-	102	7	-
11	**A3D2**	ARA3	2.2	**4.8**	7.0	-	76	6	588
12	**A3D5**	ARA3	1.8	5.7	7.4	-	80	6	**1058**
13	**A3D6**	ARA3	2.1	5.6	7.8	-	84	6	-
		BEST	**1.1**	**4.8**	**6.9**		**74**	**4**	**1058**
		WORST	**3.1**	**11.8**	**12.9**		**139**	**10**	**51**
		AVERAGE	**1.6**	**6.7**	**8.3**		**89**	**7**	**746**

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

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

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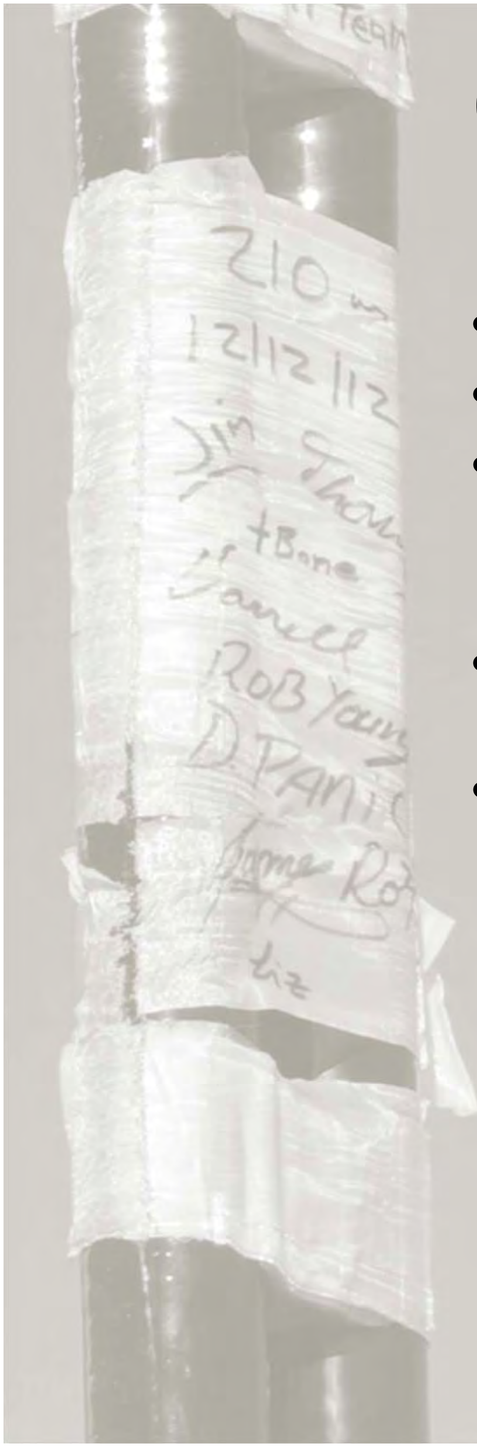
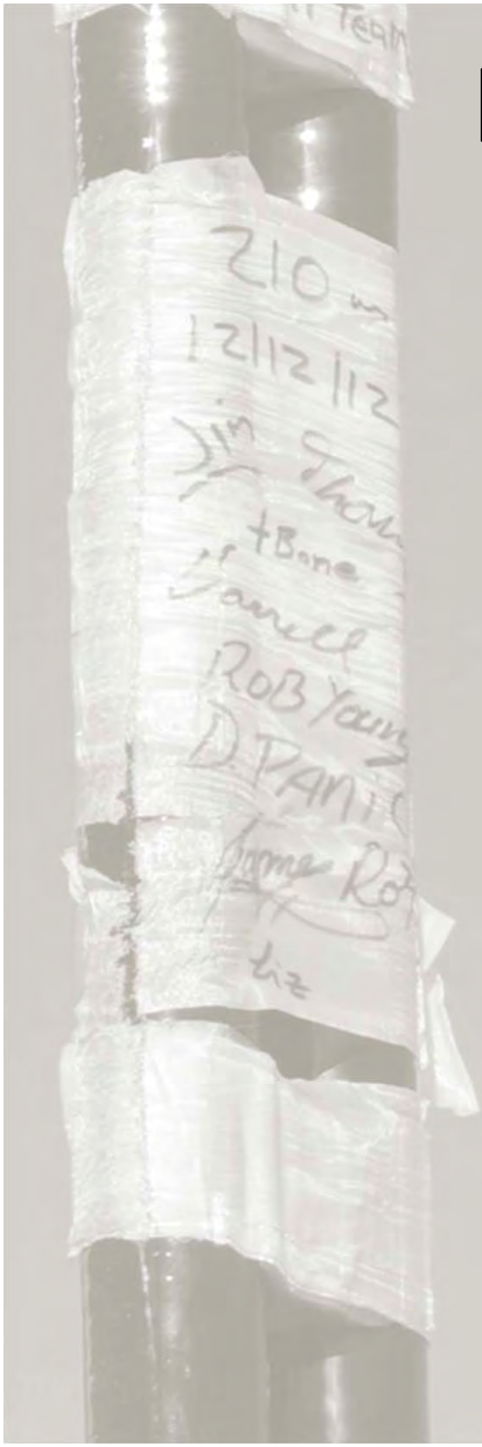
Drill Water Deliver	10 GPM at 87°C	12 GPM at 88°C	12 GPM at 81°C
% power down-hole/snow-melting	45% / 55%	100% / 0%	100% / 0%
Net Water Production per 100 meters	-2500 gal	+600 gal	+355 gal *average* +504 gal *best?*
Drilling Rate	0.34 m/min	0.6 – 1.0 m/min	0.63 m/min *average* 0.68 m/min *best*
Max Target Depth in 10 hr[1]	120 m	200 m	200 m
Time[2] to drill Φ6+", dry hole…			
to 40 meters (firn only)	1.9 hr	1 hr	1.6 hr *average* 1.1 hr *best*
to 100 meters (incl firn)	4.2 hr	2 hr	4.0 hr *average est.* 2.8 hr *best est.*
to 200 meters (incl firn)	17 hr	5 hr	8.3 hr *average* 5.9 hr *best of the best*

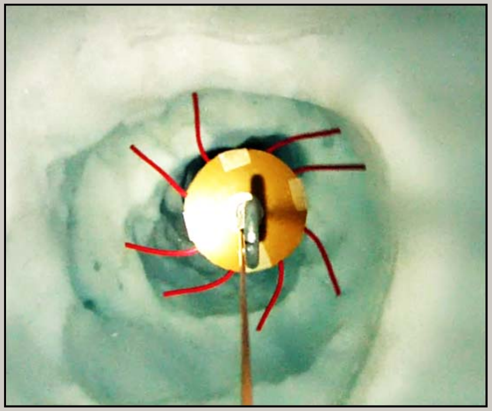


Operations

- 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

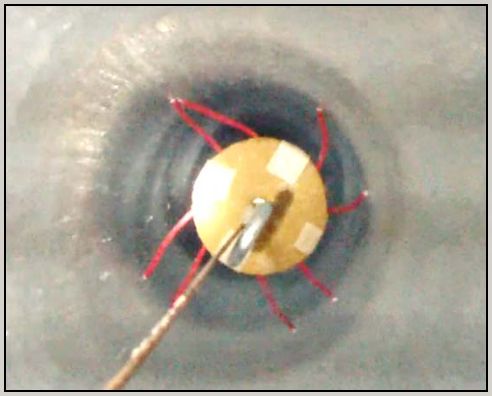
0-40m

Oversized, ragged, offshoots

TRANSITION ZONE

40-120m

Frosty, post-drill ice structures

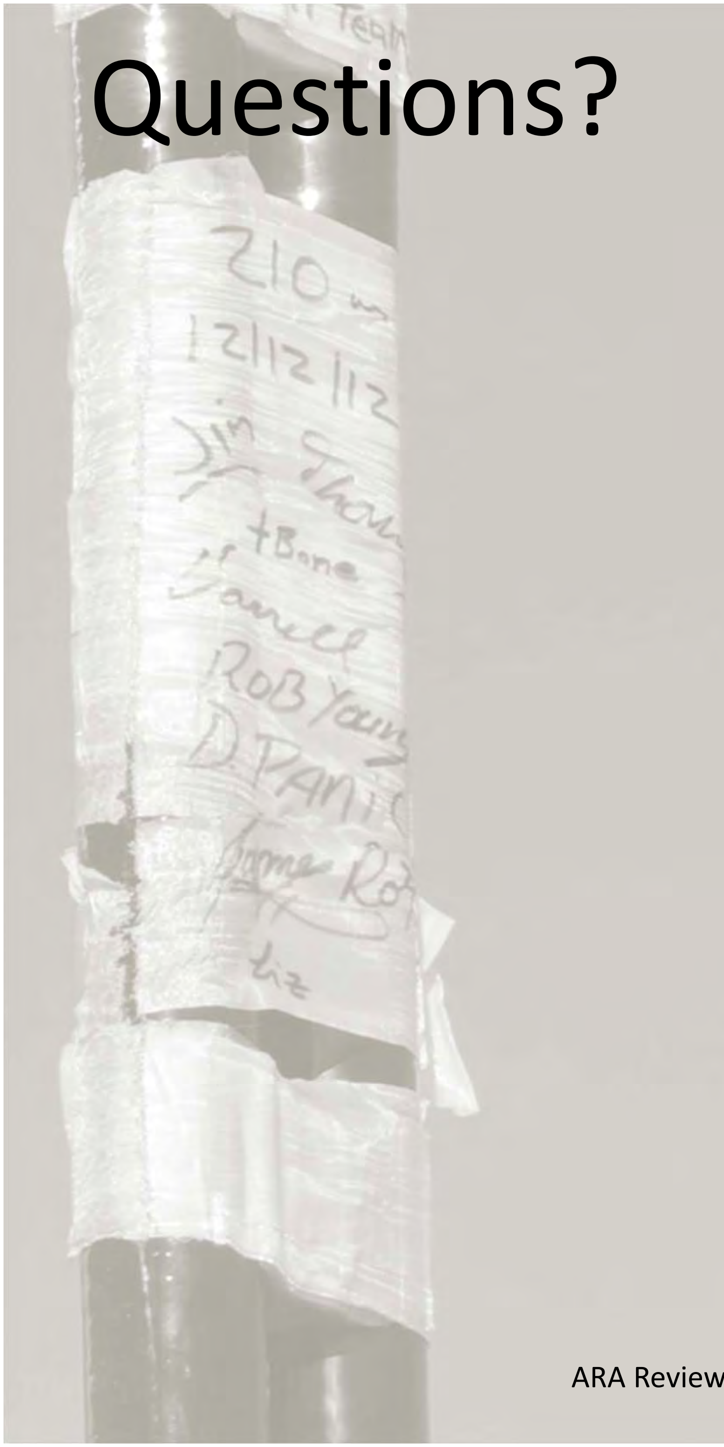


DEEP ICE

120-200m

Smooth and uniform

Questions?

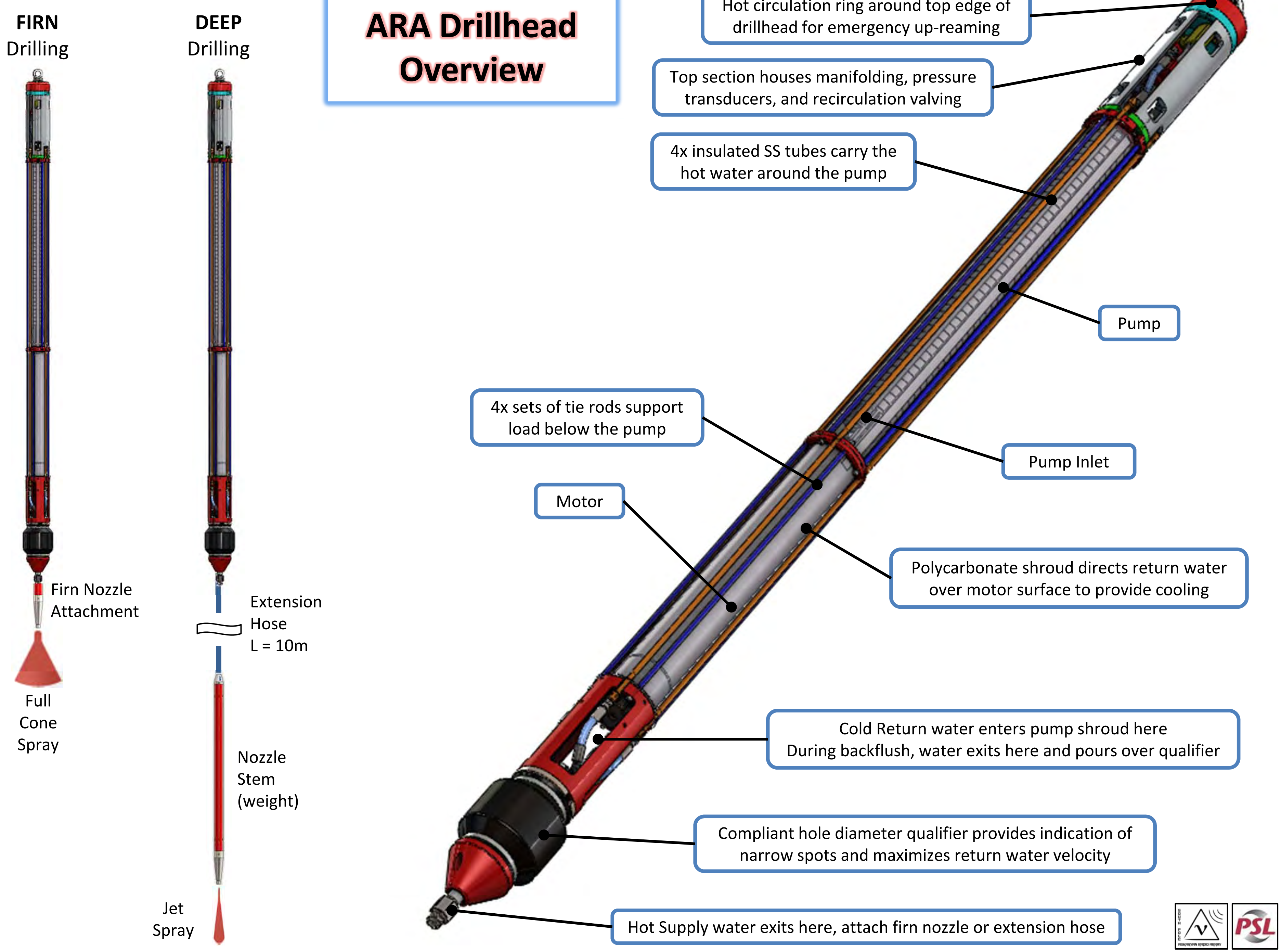


210m
12/12/12
+Bone
Darrell
ROB Young
D.PANIC
Liz

210m
12/31/12
A3D6
Jim
Rob Young
Darrell
Dave Panic
BERT
210m
12/12/12
+Bone
Darrell
ROB Young
SPARE

Additional Slides…

ARA Drillhead Overview



ARA Hose Reel Overview

Hose and cable bundle

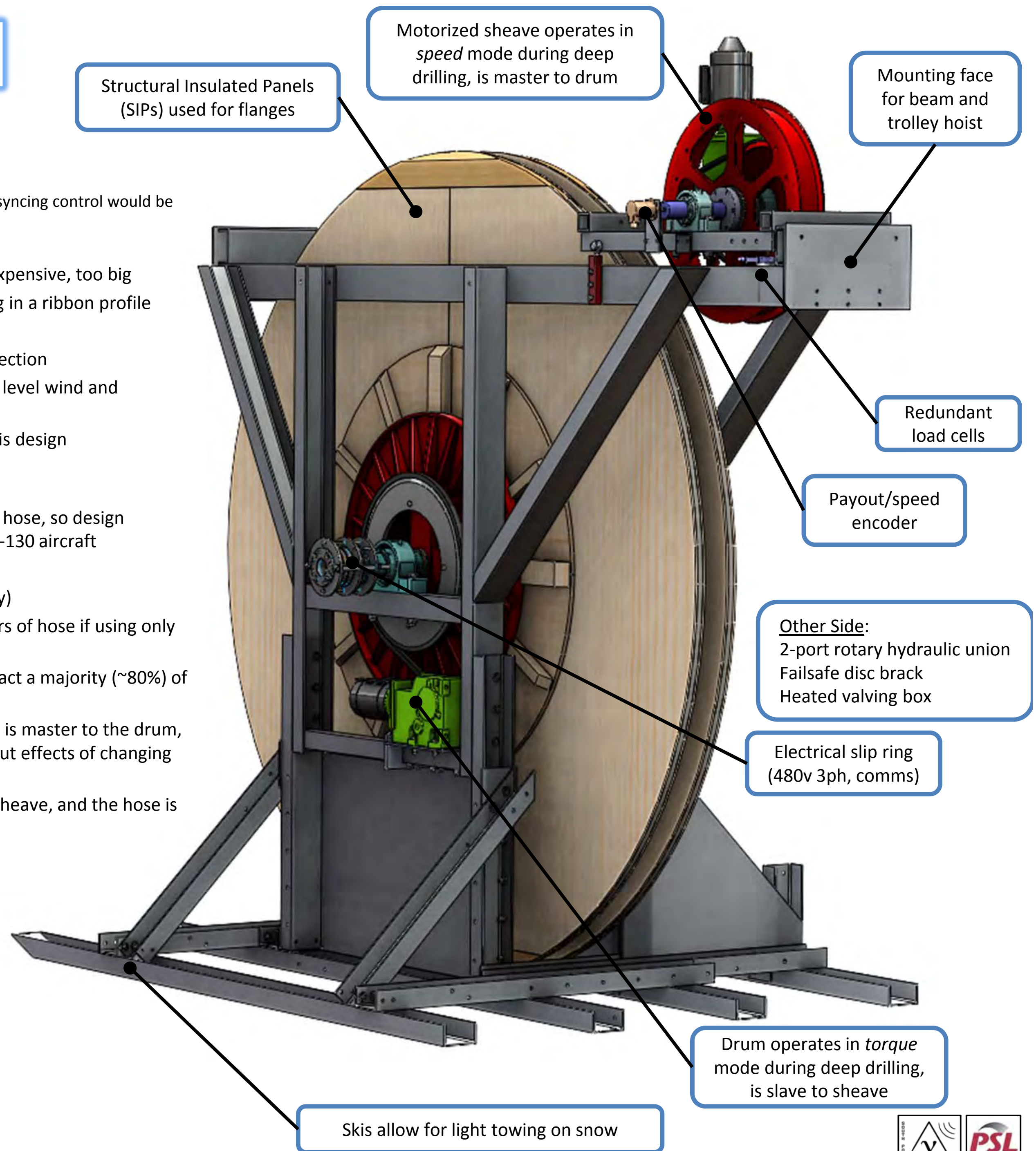
- 2x hoses and 1x combo cable
- Multi-reel joined at hole not a solution
  - Load to be shared amongst all 3 members, intricate syncing control would be required
  - Extra task at hole of joining/separating members
- Manufactured umbilical with round cross-section too expensive, too big
- Decided to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

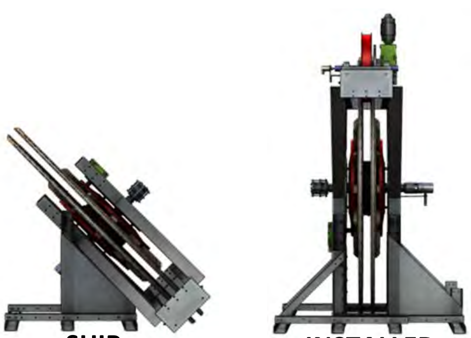
Single width spiral configuration

- 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 succesfully utilized this design
  - Rapid Air Movement (RAM) Drill
  - Independent Firn 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 bouyancy)
- 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

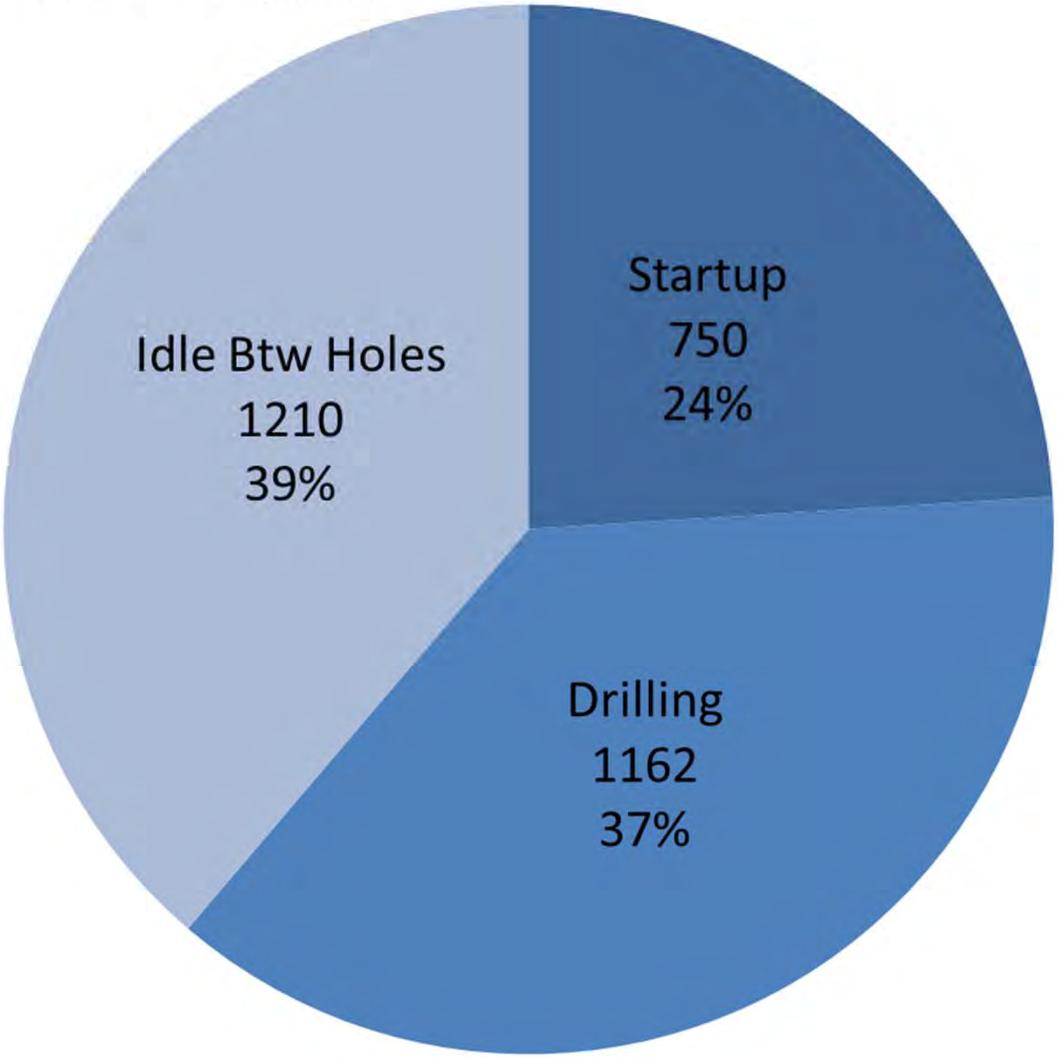




SHIP Position → **INSTALLED** Position

ARA 12-13 Fuel (AN8) by Phase

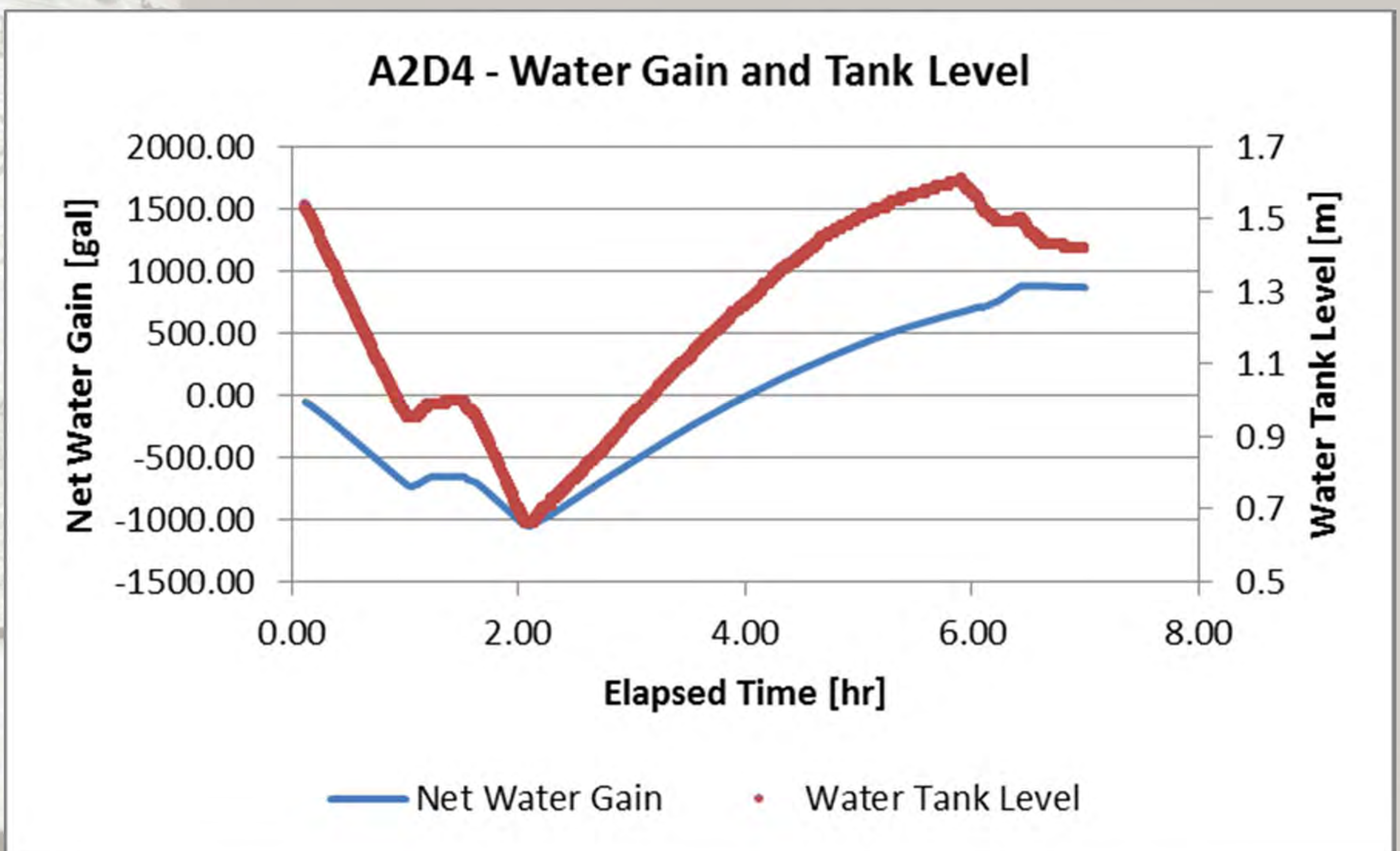
Includes all AN8 fuel usage (drilling, heat, vehicles)
Amounts in gallons

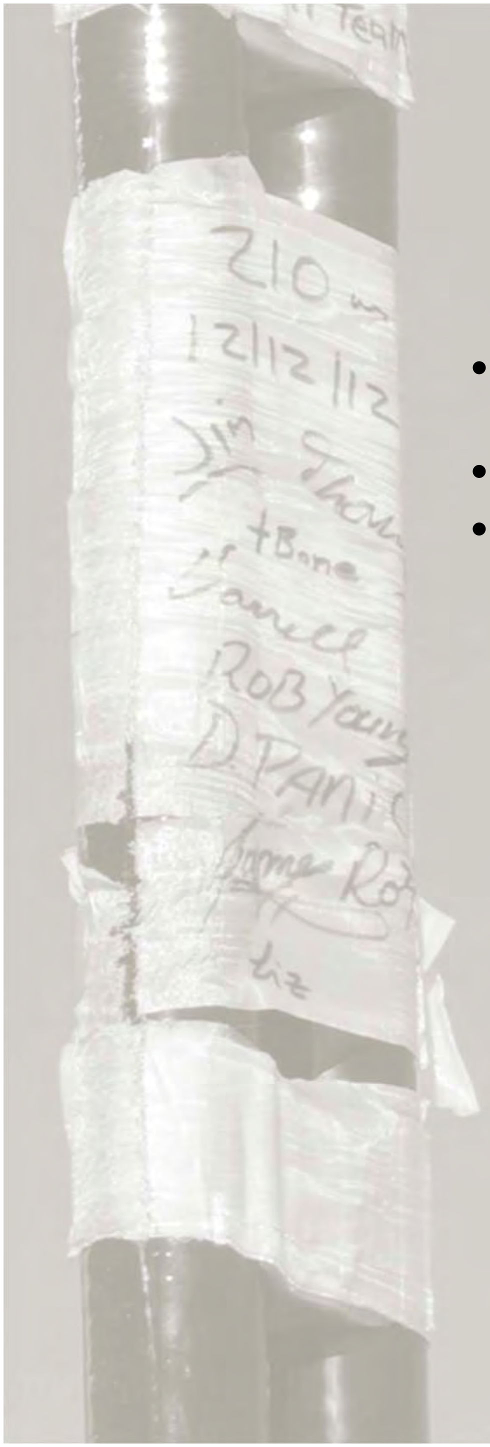


Total Season Fuel
3122 gal AN8
90 gal Gasoline*

*Gasoline amount does not include vehicle nor snowmobile usage

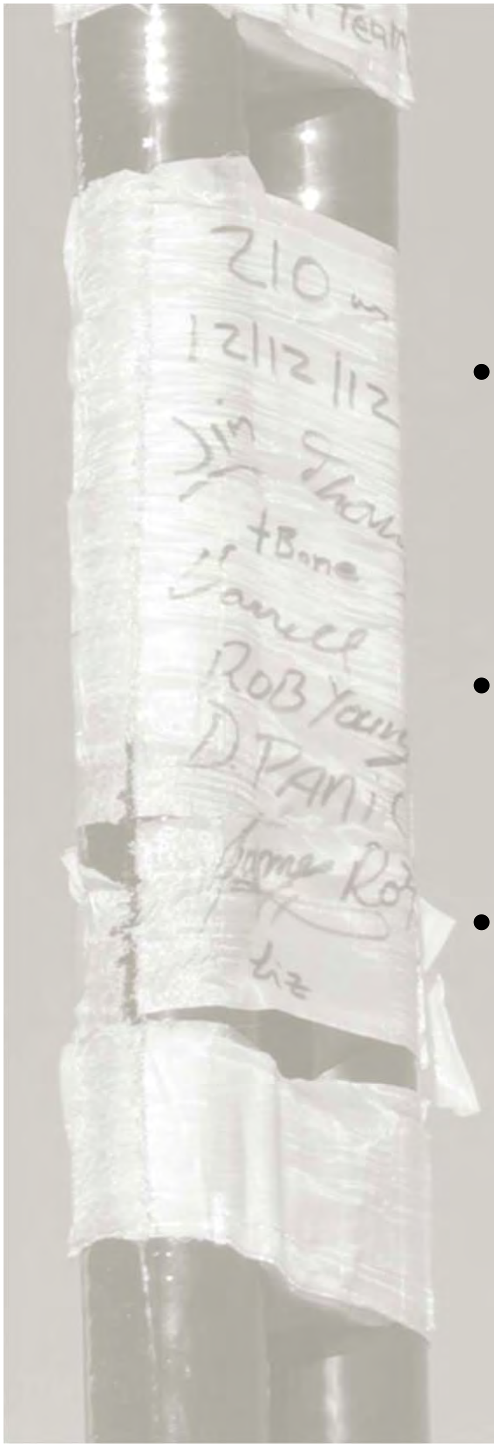
Water Usage/Production





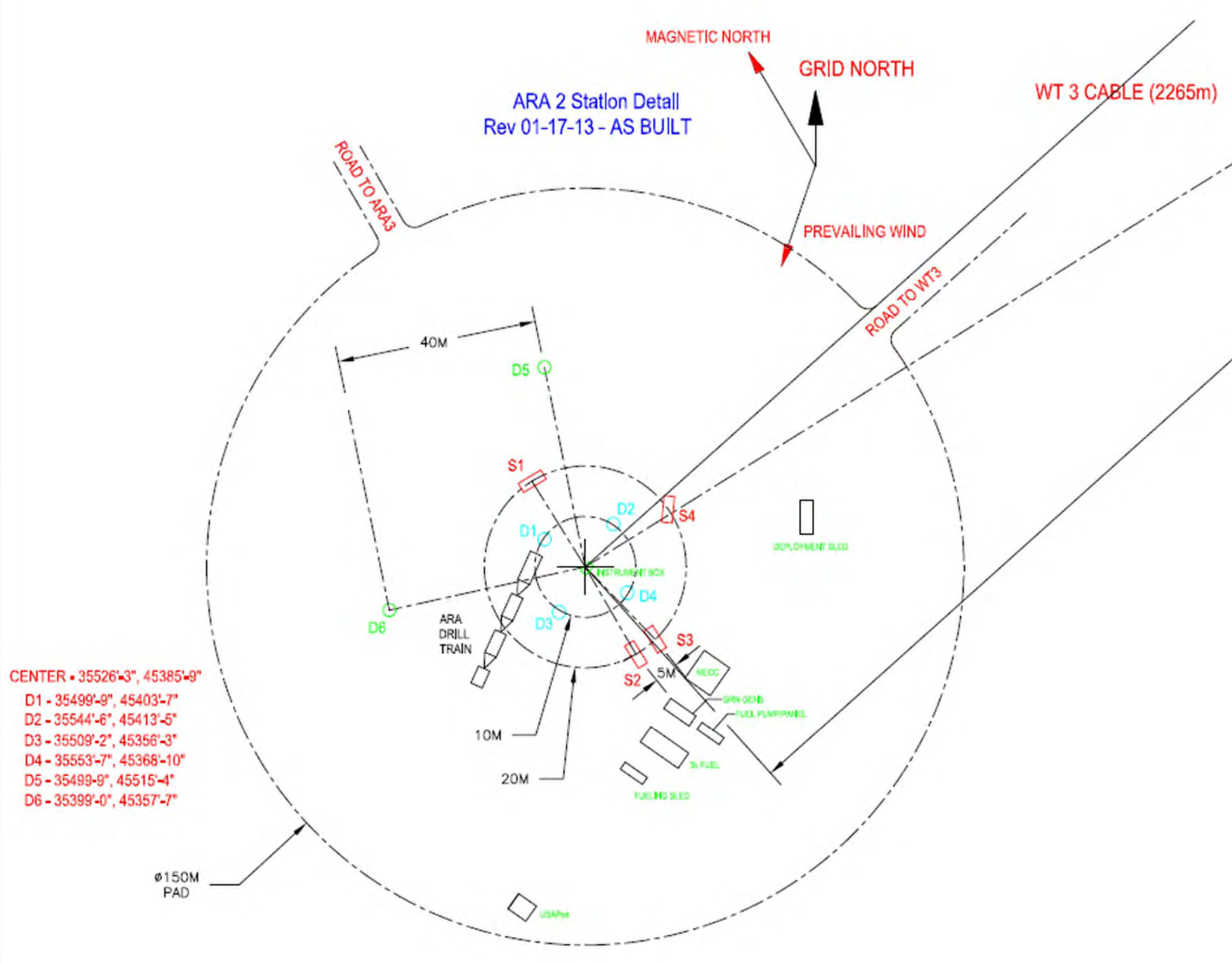
Why Hot Water?

- 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



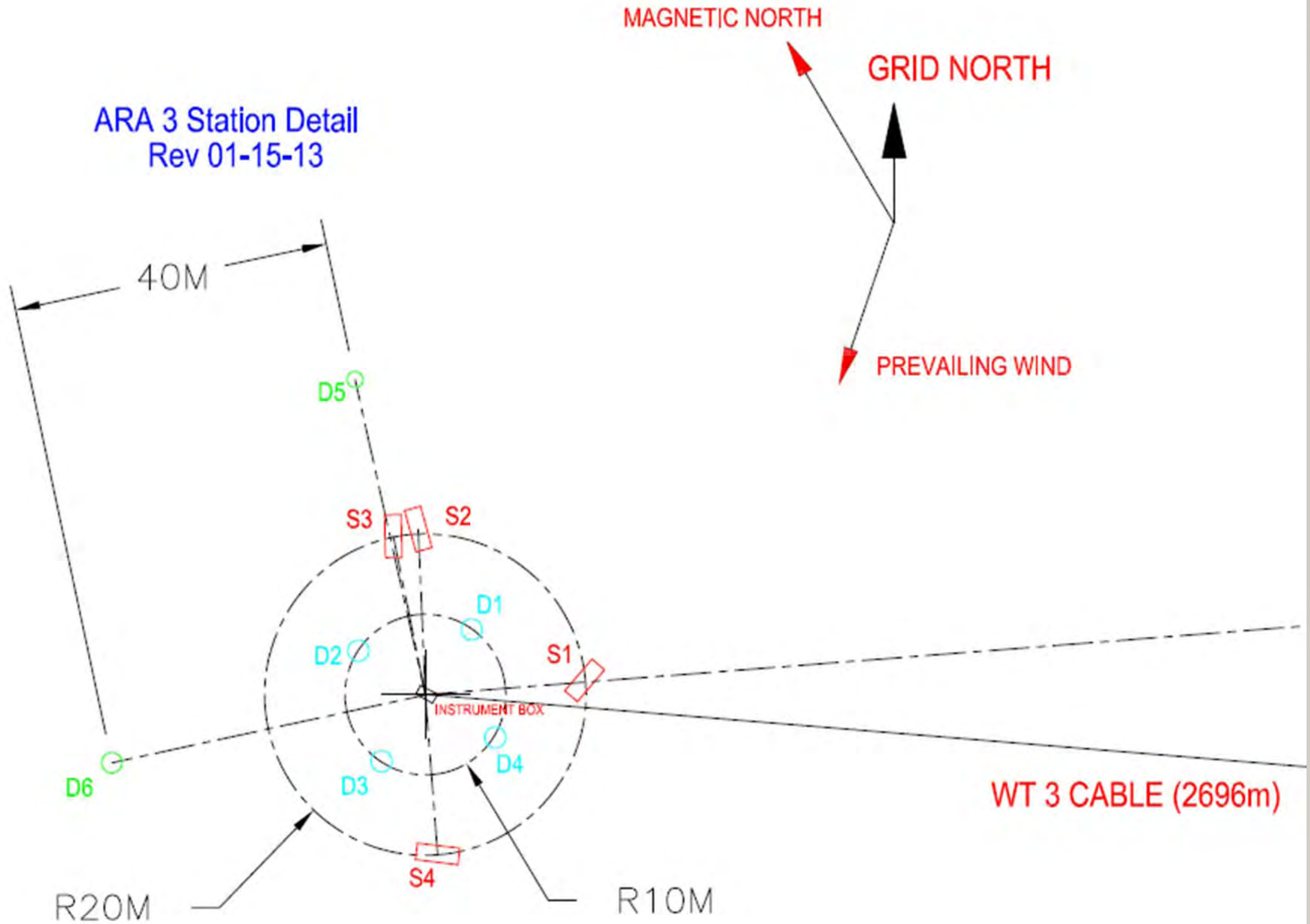
Modeling

- 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.



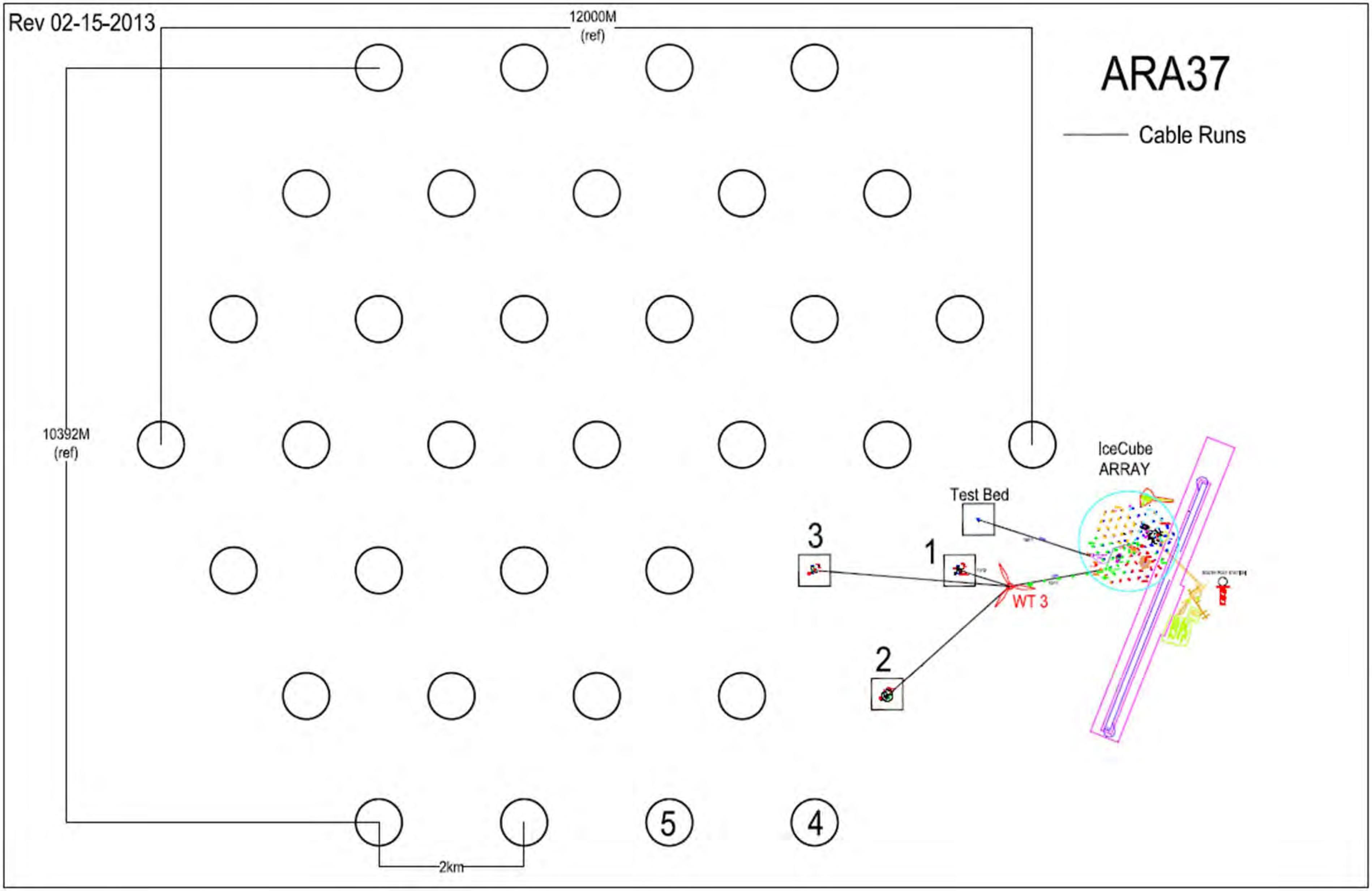
ARA 2 Station Detail
Rev 01-17-13 - AS BUILT
MAGNETIC NORTH
GRID NORTH
WT 3 CABLE (2265m)
ROAD TO ARA3
PREVAILING WIND
ROAD TO WT3
40M
D5
S1
D2
S4
D1
INSTRUMENT BOX
DEPLOYMENT SLED
D4
D6
D3
ARA
DRILL
TRAIN
S3
5M
S2
10M
20M
FUELING SLED
CENTER - 35526'-3", 45385'-9"
D1 - 35499'-9", 45403'-7"
D2 - 35544'-6", 45413'-5"
D3 - 35509'-2", 45356'-3"
D4 - 35553'-7", 45368'-10"
D5 - 35499-9", 45515'-4"
D6 - 35399'-0", 45357'-7"
ø150M
PAD

ARA 3 Station Detail
Rev 01-15-13



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



Rev 02-15-2013
12000M
(ref)
ARA37
Cable Runs
10392M
(ref)
IceCube
ARRAY
Test Bed
3
1
WT 3
2
5
4
2km