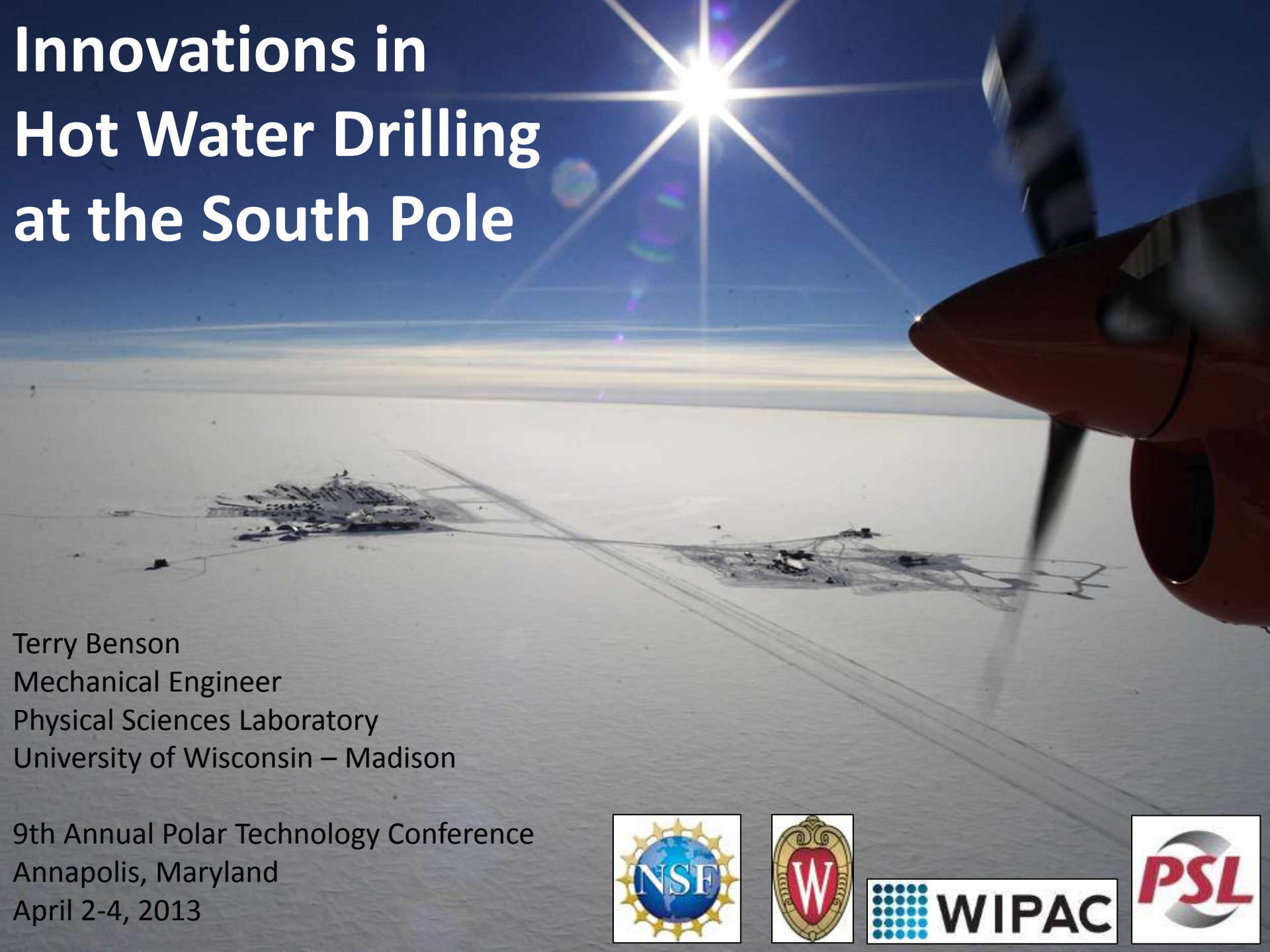
Innovations in Hot Water Drilling at the South Pole

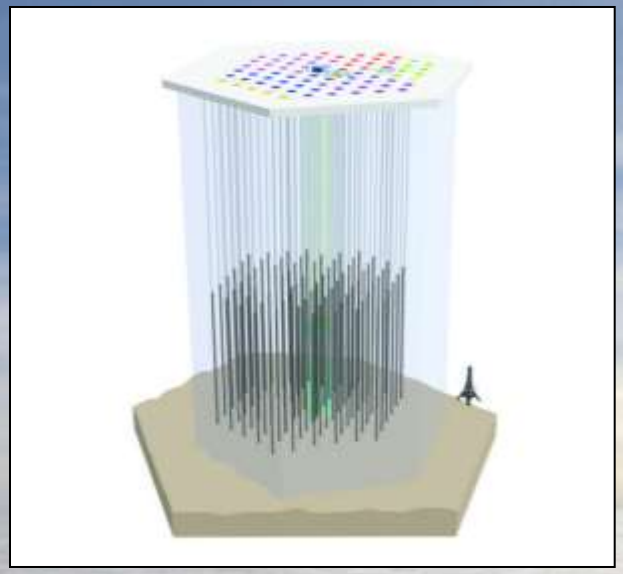


Terry Benson
Mechanical Engineer
Physical Sciences Laboratory
University of Wisconsin – Madison

9th Annual Polar Technology Conference
Annapolis, Maryland
April 2-4, 2013

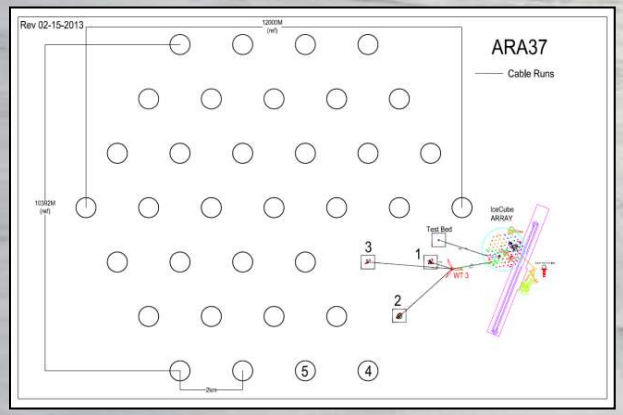
Two South Pole Neutrino Detectors

Two Hot Water Drilling Systems



IceCube Detector
In Operation
Construction 2004-2011

<u>Enhanced Hot Water Drill</u>
5 MW
ϕ60cm x 2500m in 48hr

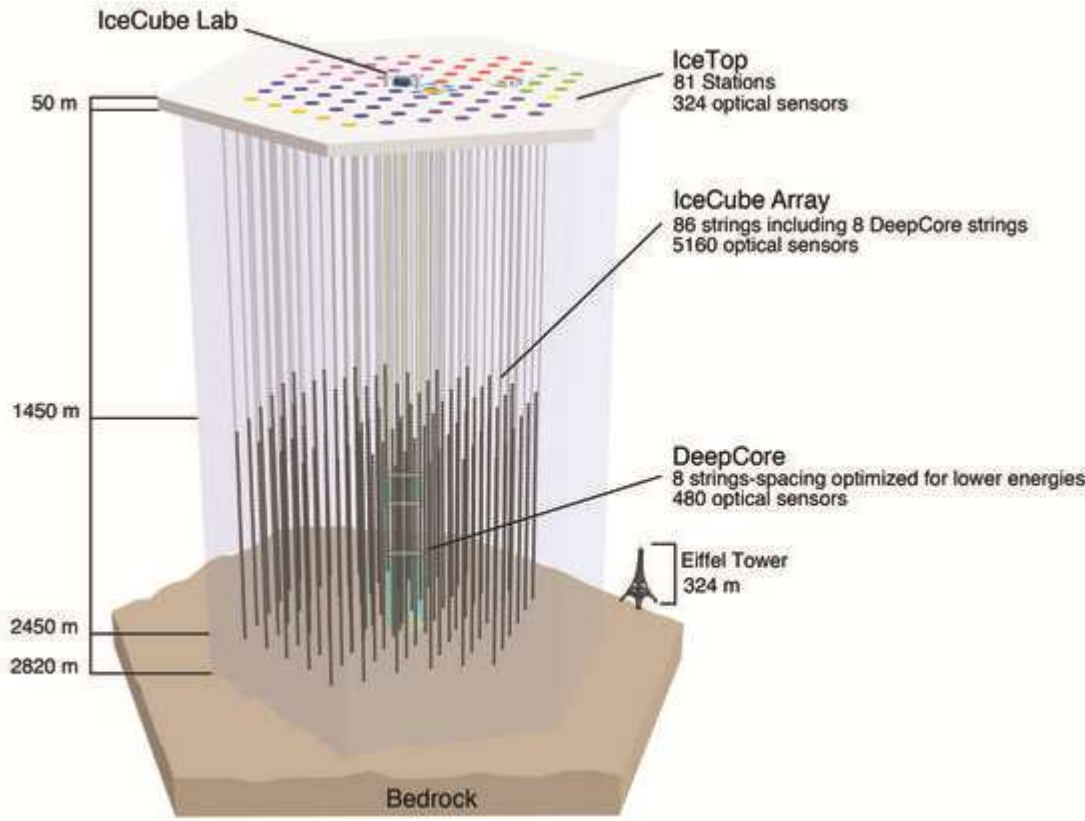


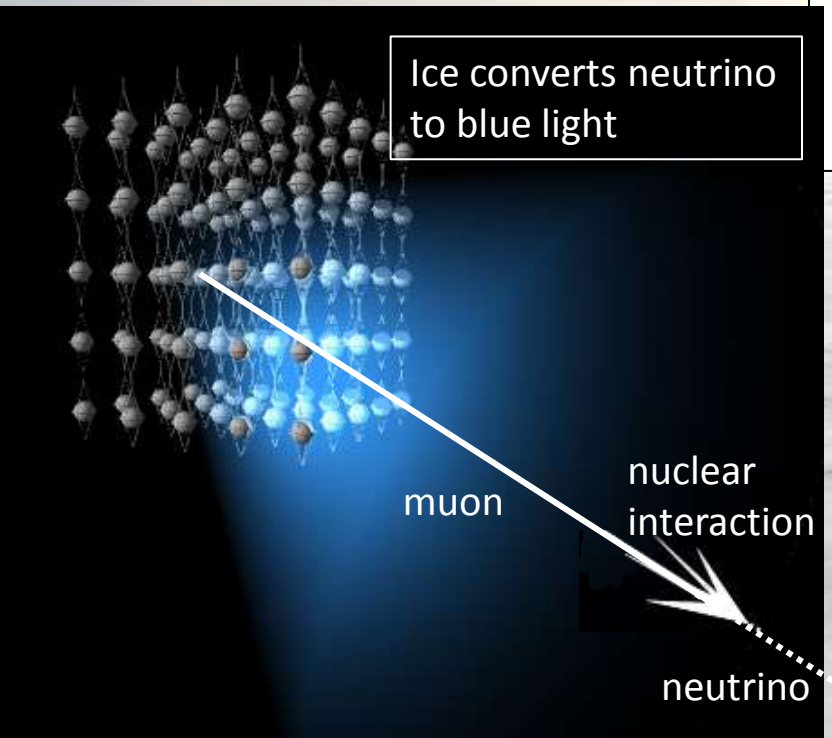
Askaryan Radio Array (ARA)
Under Construction

<u>ARA Hot Water Drill</u>
300 kW, mobile
ϕ16cm x 200m in 10hr

IceCube Overview

- 1 km^3 neutrino telescope
- Transforms 1 billion tons of ice into a particle physics detector





WHY?

- New window into the cosmos
- Discovery machine

WHY THE SOUTH POLE?

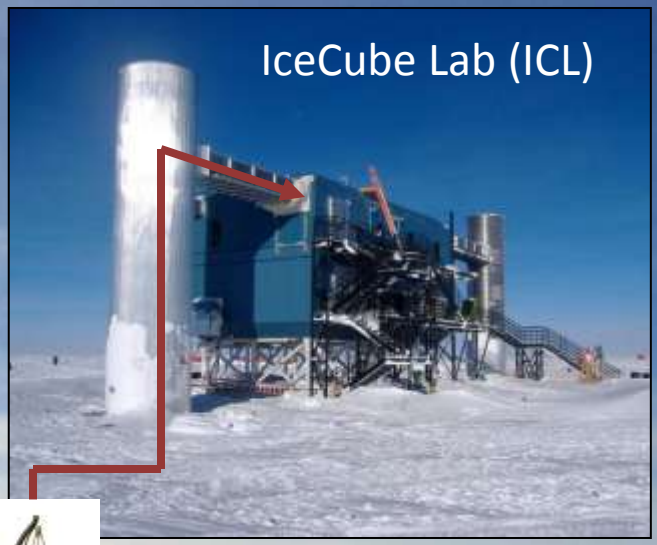
- Lots of ICE
  - Transparent and clear
  - Large volume
- Sufficient infrastructure

More Info:

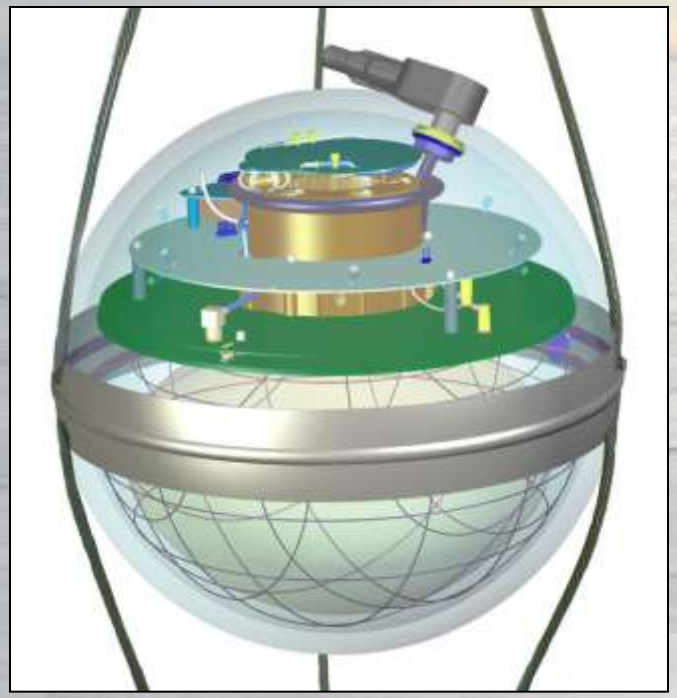
PTC 2009 (Madison) – Francis Halzen *Overview of the IceCube Project*

IceCube Overview – INSTRUMENTATION

- Digital Optical Module
  - Down-facing Photomultiplier Tube (PMT)
  - On-board computer
  - Glass sphere (ϕ14”, 10000psi+)
- Cables (downhole and surface)
- IceCube Lab
  - Data collection, processing, storage, data link to North



Digital Optical Module (DOM)



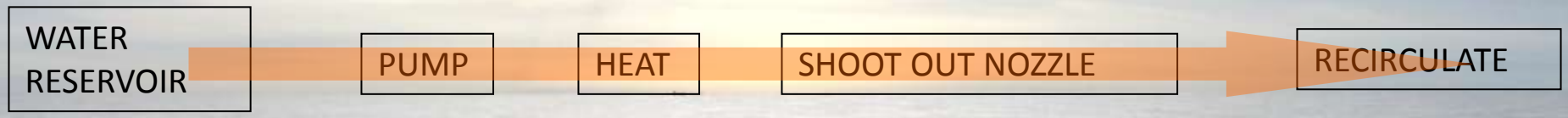
DOM being deployed into hole

60 DOMs per String

Enhanced Hot Water Drill (EHWD) Requirements

Why Hot Water?

- Hot Water + Ice = Hole
- *Fast*
- Need a water-filled hole
  - DOMs freeze in and become optically coupled with ice sheet
  - Fluid supports hole so it doesn't collapse in on itself
  - Allows us to circulate water



System Requirements

- 86 holes, each 60 cm (24 in) in diameter and 2.5 km (1.6 miles) deep
- 17.2 million gallons of ice to melt!
- 7 field seasons (2004-2011)
- Compatible with South Pole environment and logistics
- Co-support deployment of in-ice instrumentation

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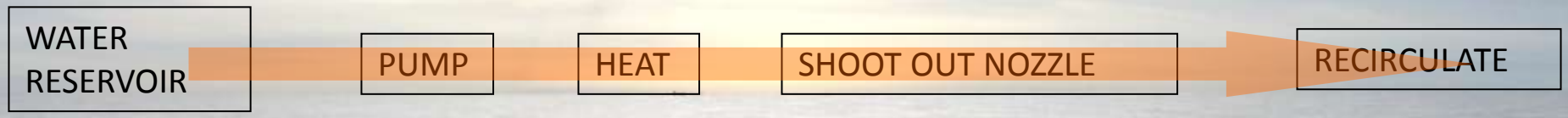

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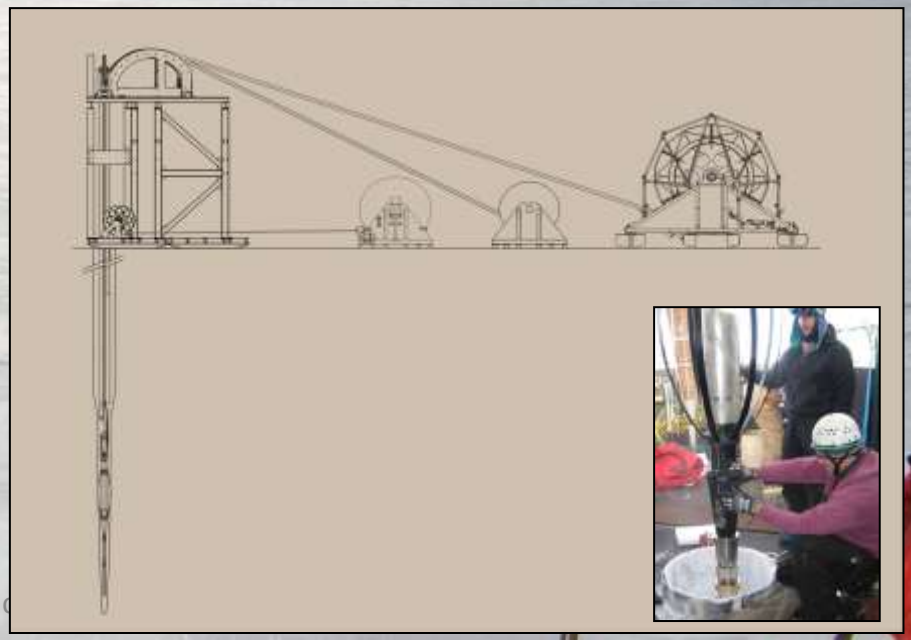
FUEL EFFICIENCY IS A DESIGN DRIVER!

Enhanced Hot Water Drill (EHWD) Design

WATER RESERVOIR → PUMP → HEAT → SHOOT OUT NOZZLE → RECIRCULATE



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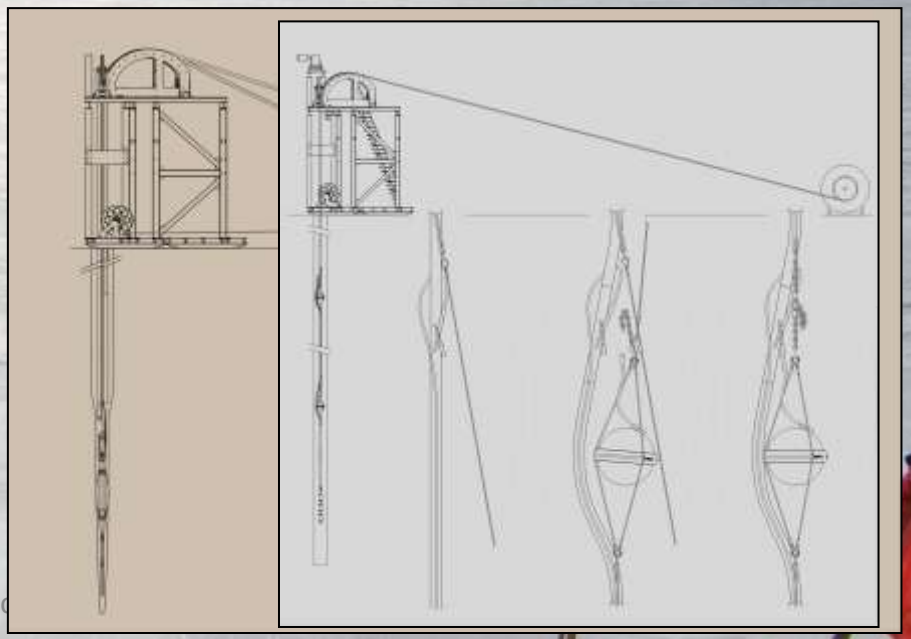

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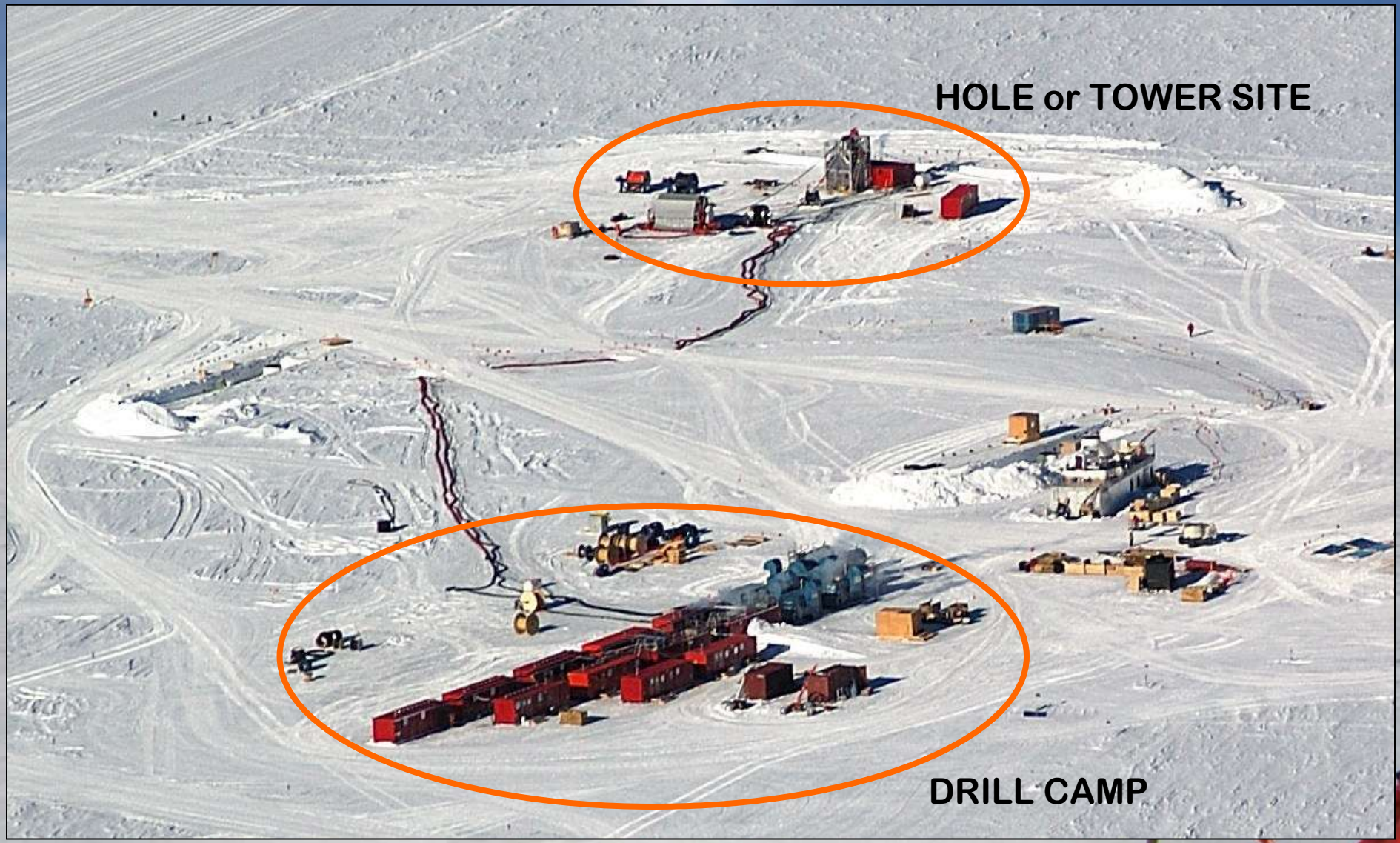
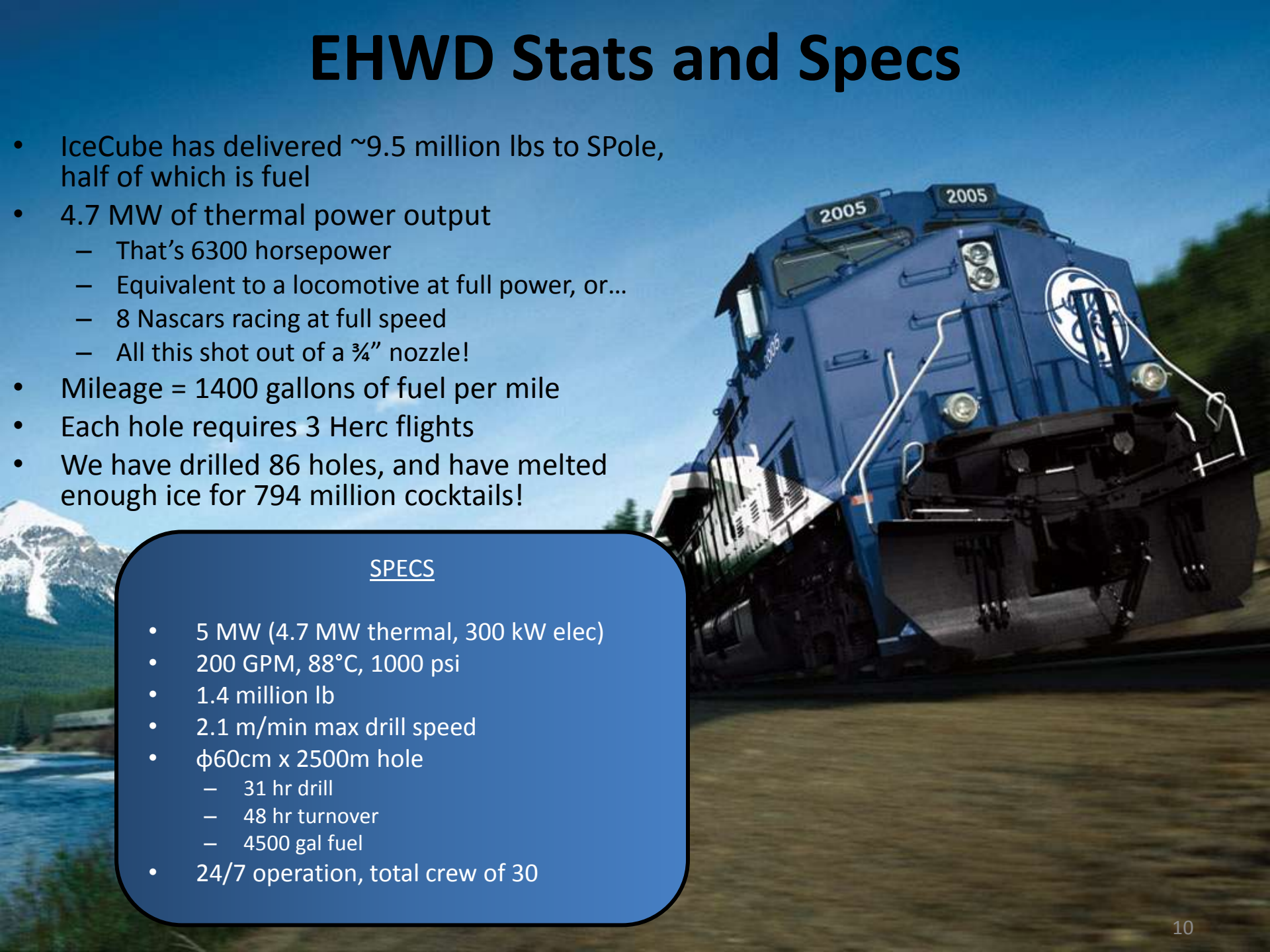


EHWD Stats and Specs

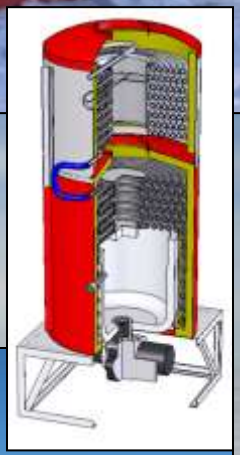
- IceCube has delivered ~9.5 million lbs to SPole, half of which is fuel
- 4.7 MW of thermal power output
  - That's 6300 horsepower
  - Equivalent to a locomotive at full power, or…
  - 8 Nascars racing at full speed
  - All this shot out of a ¾" nozzle!
- Mileage = 1400 gallons of fuel per mile
- Each hole requires 3 Herc flights
- We have drilled 86 holes, and have melted enough ice for 794 million cocktails!



SPECS

- 5 MW (4.7 MW thermal, 300 kW elec)
- 200 GPM, 88°C, 1000 psi
- 1.4 million lb
- 2.1 m/min max drill speed
- ϕ60cm x 2500m hole
  - 31 hr drill
  - 48 hr turnover
  - 4500 gal fuel
- 24/7 operation, total crew of 30

Enhanced Hot Water Drill (EHWD) Notables and Takeaways



Notables

- Advanced computer control system
- High-efficiency water heaters, 92% HHV
- Instrumented drillhead
- Thermal modeling and drill strategy
- Giant hose reel with continuous custom hose
- Independent firn drill

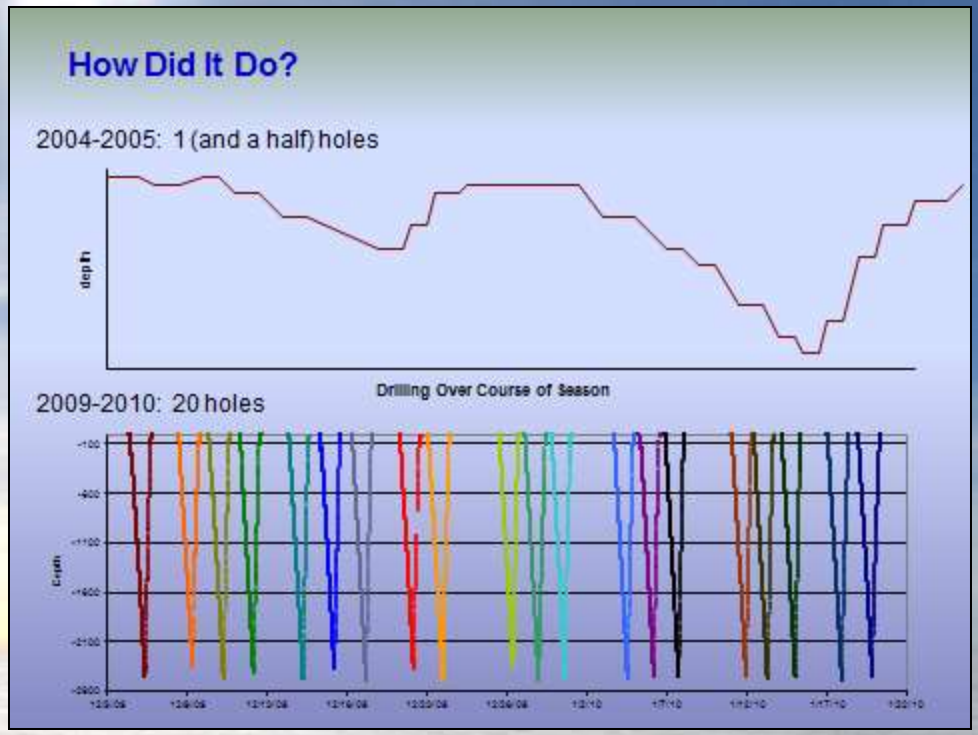
Takeaways

- Wide range of electric and mechanical systems implemented at South Pole
- Hole modeling and freeze back tools
- Hose and its challenges
- Nozzle velocity very important
- Independent firn drill incredibly valuable
- Generator heat recovery
- Rodwell strategies
- Strong safety and fuel-conservation cultures make a difference
- Staffing – RETAIN EXPERIENCE

Enhanced Hot Water Drill (EHWD) Performance

Hole Profiles (depth vs time)

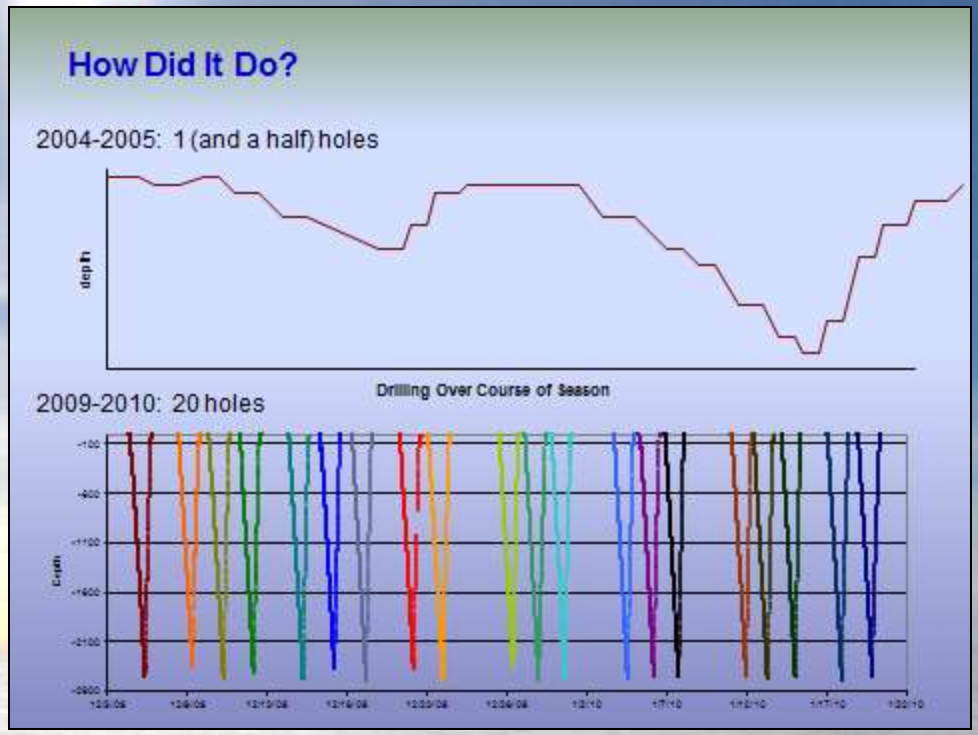
- Good indication of performance



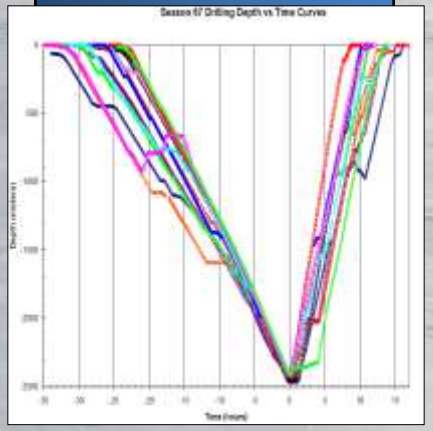
Enhanced Hot Water Drill (EHWD) Performance

Hole Profiles (depth vs time)

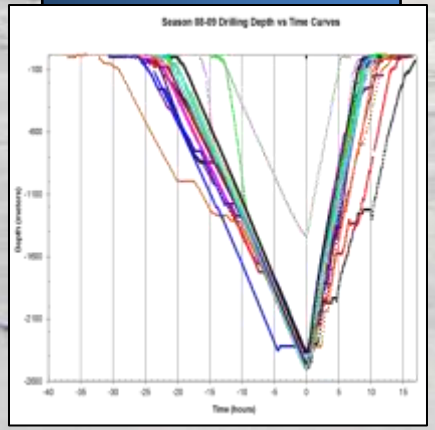
- Good indication of performance
- Trend highlights reliability and experience



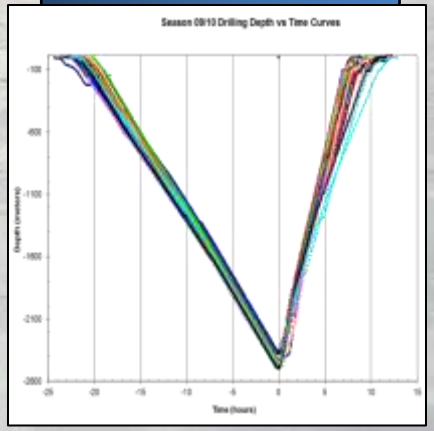
2006-07: 13 holes



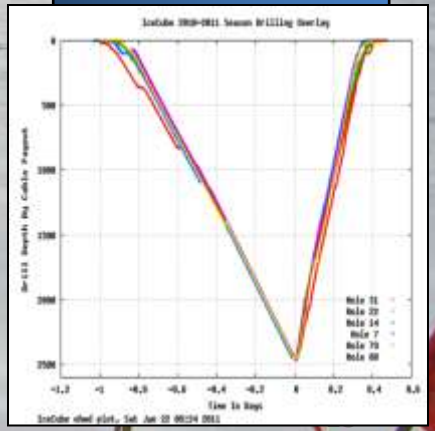
2008-09: 19 holes



2009-10: 20 holes



2010-11: 6 holes



IceCube Detector

Construction completed Dec 2010

EHWD parted out, but most equipment still @ South Pole (under NSF custodianship)

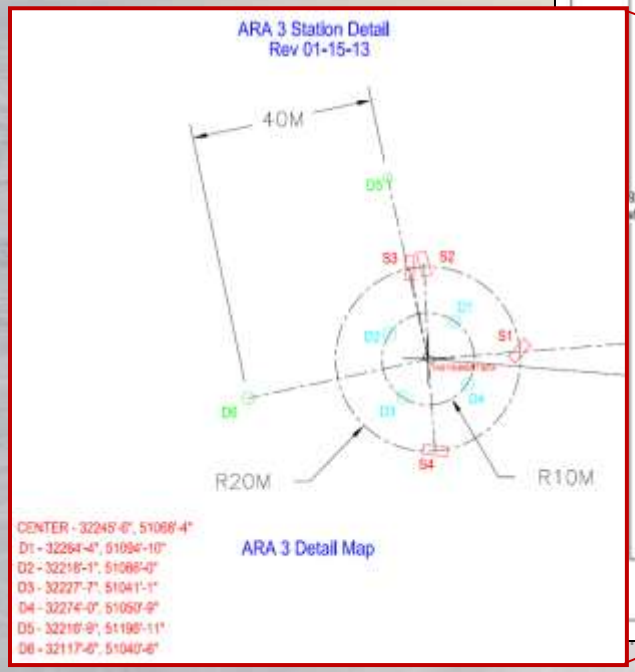
ARA

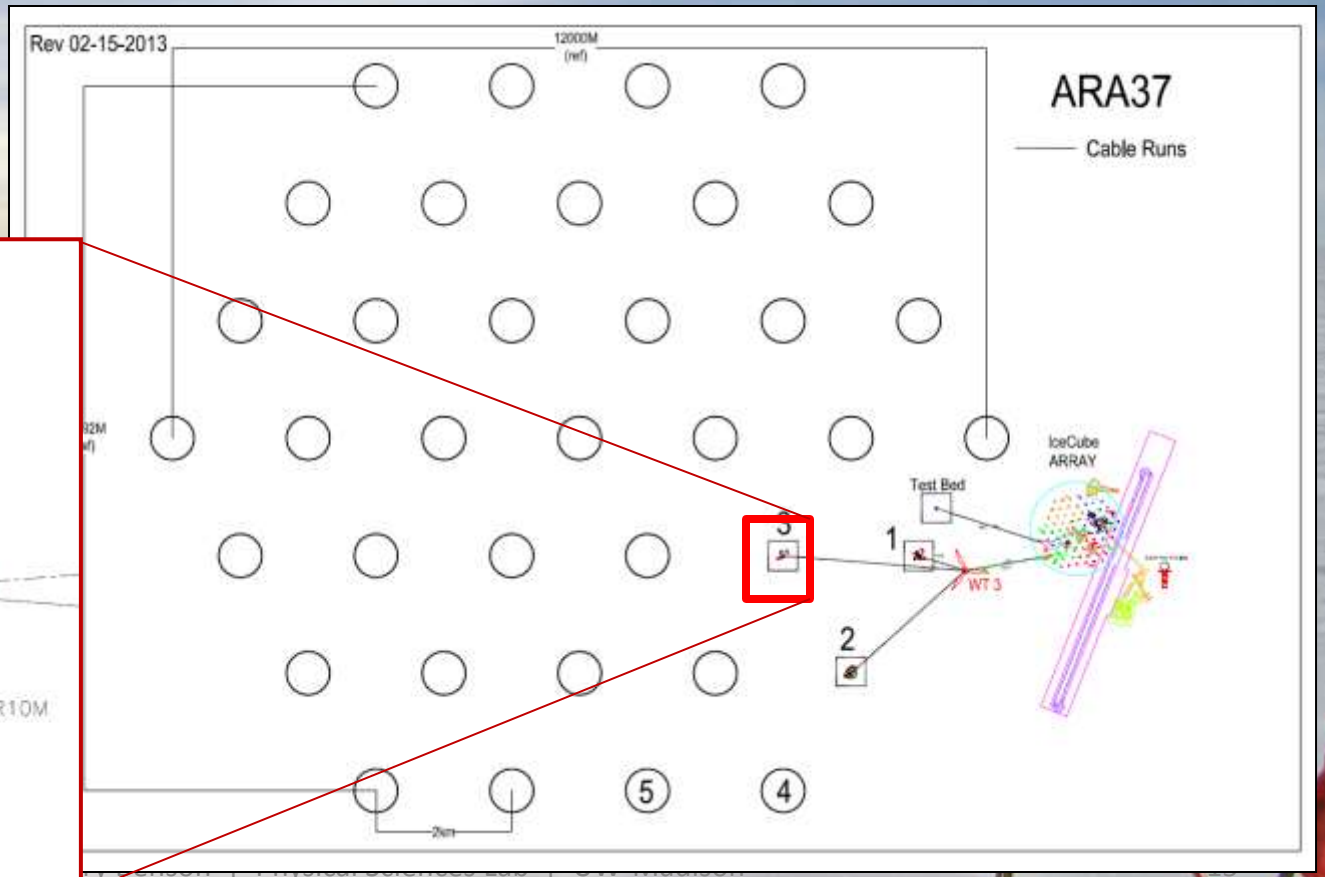
Proof of concept stage began Jan 2011

New drill

ARA Overview

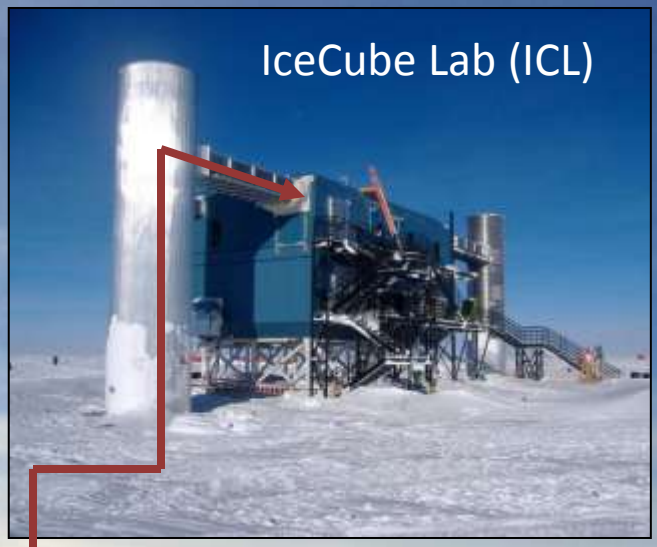
- ARA = Askaryan Radio Array = Neutrino Telescope
- Detects *RADIO* signature from neutrino interaction with ice
- Very large area (100 km^2)
  - ARA37 = 37 “Stations”
  - 6 holes/station
  - 222 holes
- Closely coupled with IceCube





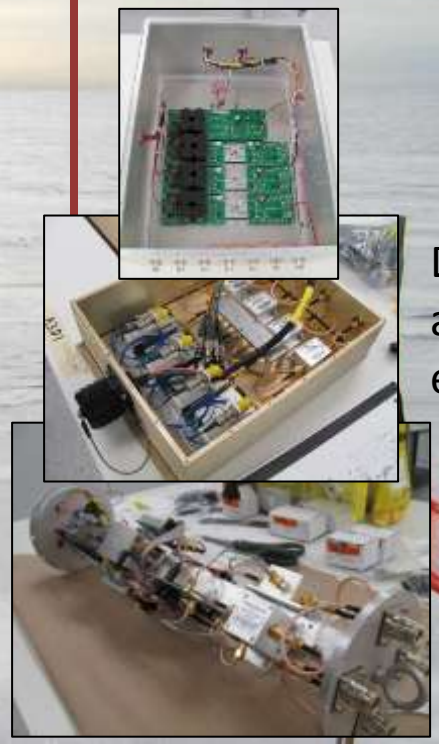
ARA Overview - INSTRUMENTATION

- Antennas
  - Vertically polarized (2 per hole)
  - Horizontally polarized (2 per hole)
- Electronics
  - Downhole
  - Surface
- Deployment kit and cables
- IceCube Lab
  - Data collection, processing, storage, data link to North



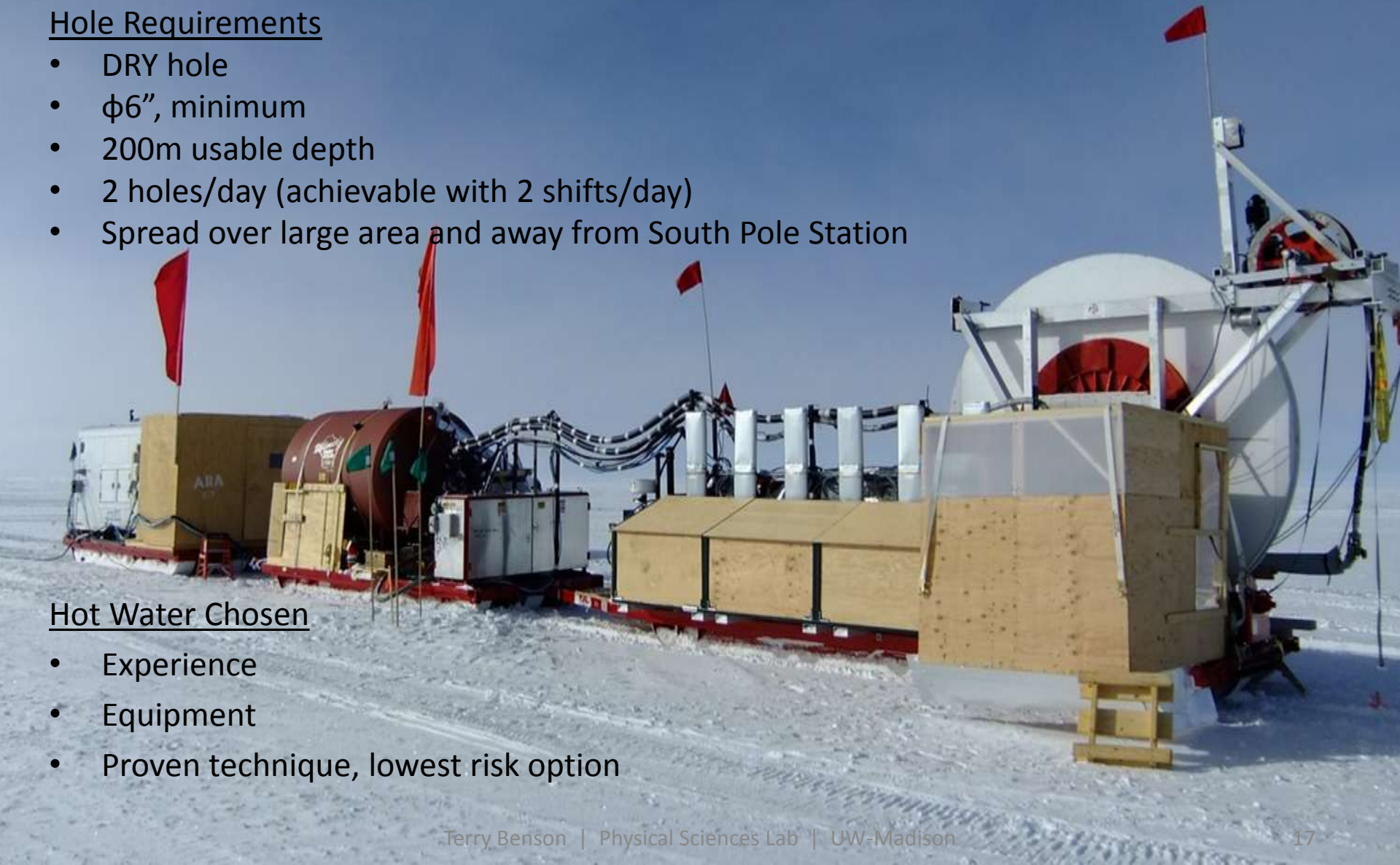
Antennas
2 pairs/hole

Antenna being
deployed into hole



Down-hole
and surface
electronics

ARA Hot Water Drill (ARAHWD) Requirements



Hole Requirements

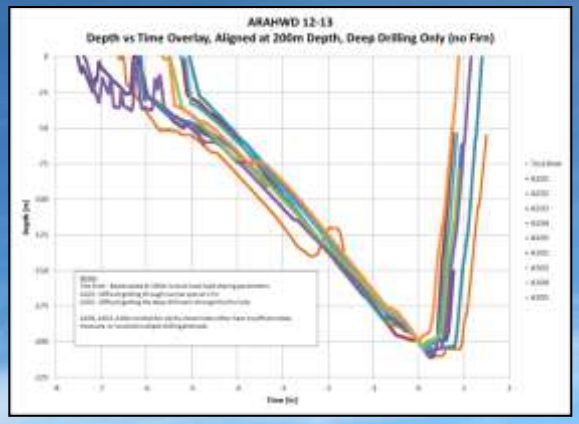
- DRY hole
- ϕ6”, minimum
- 200m usable depth
- 2 holes/day (achievable with 2 shifts/day)
- Spread over large area and away from South Pole Station

Hot Water Chosen

- Experience
- Equipment
- Proven technique, lowest risk option

ARA HOT WATER DRILL

3 sled train configuration, 34k lb dry weight
300 kW thermal power
12 gpm, 85°C, 1000 psi
ϕ16cm x 200m DRY hole in 7hr
crew of 5/shift



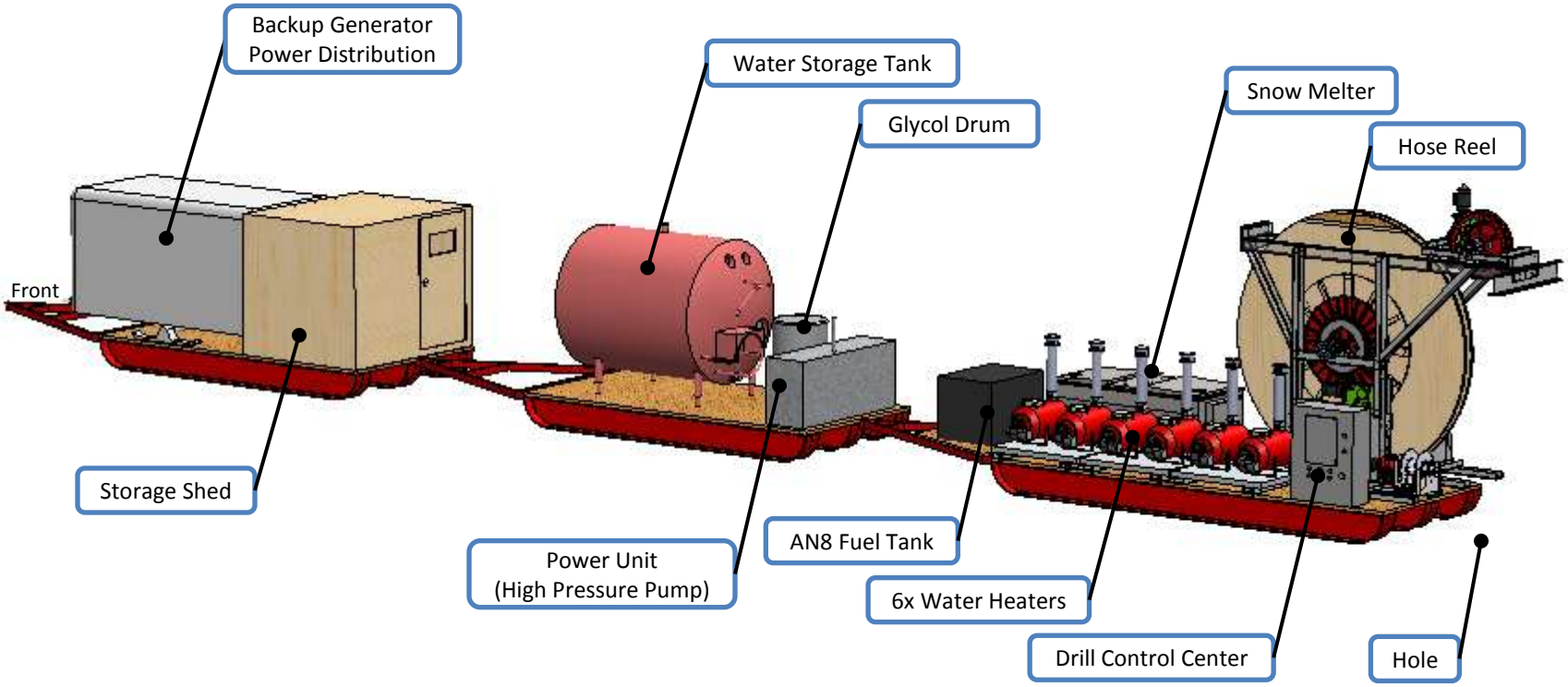
Overlay of 2012-13 hole profiles

- Askaryan Radio Array (ARA): Neutrino detector under construction at the South Pole
- Hole Requirements: ϕ16cm x 200m depth, DRY, 2 holes/day (with 2 shifts)
- New Technique: Pump hole dry during drilling process, pump travels with drillhead
- Successful 2012-13 field season
  - Inaugural season for updated system and new drill method
  - 12x production holes (12 planned)
  - All ARA detector instrumentation successfully deployed
  - 1 hole per day with 1 shift (12 hour shifts last season, 10 hour shifts within reach)

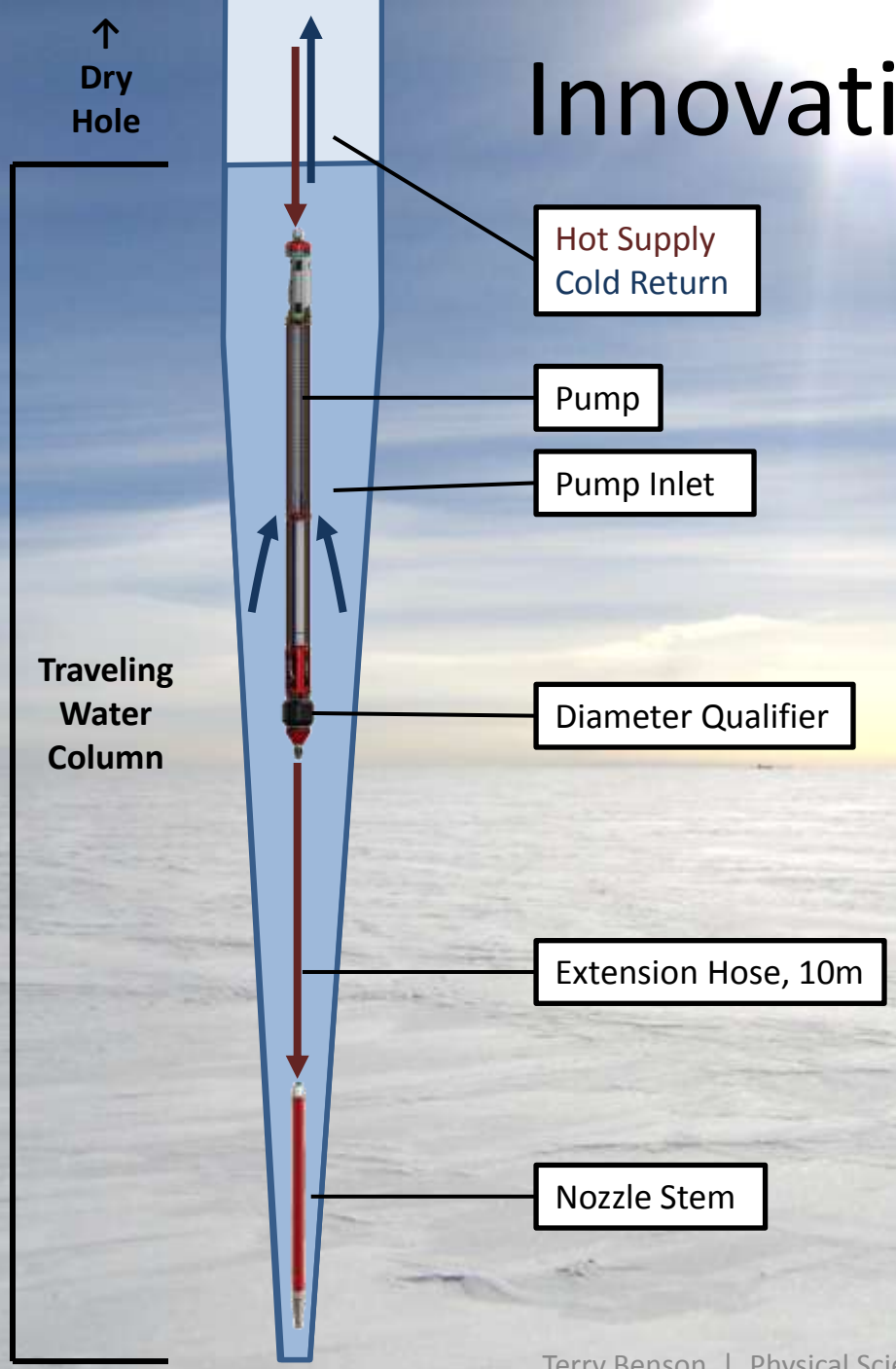
PSL WIPAC

T. Benson, PSL

ARA Drill Train



Innovation in Technique



<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 from lost water / snow melting method
- Leaves dry hole above
  - No freezeback!
  - 1 step = faster production rate

ARA Hot Water Drill (ARAHWD) Challenges and Takeaways

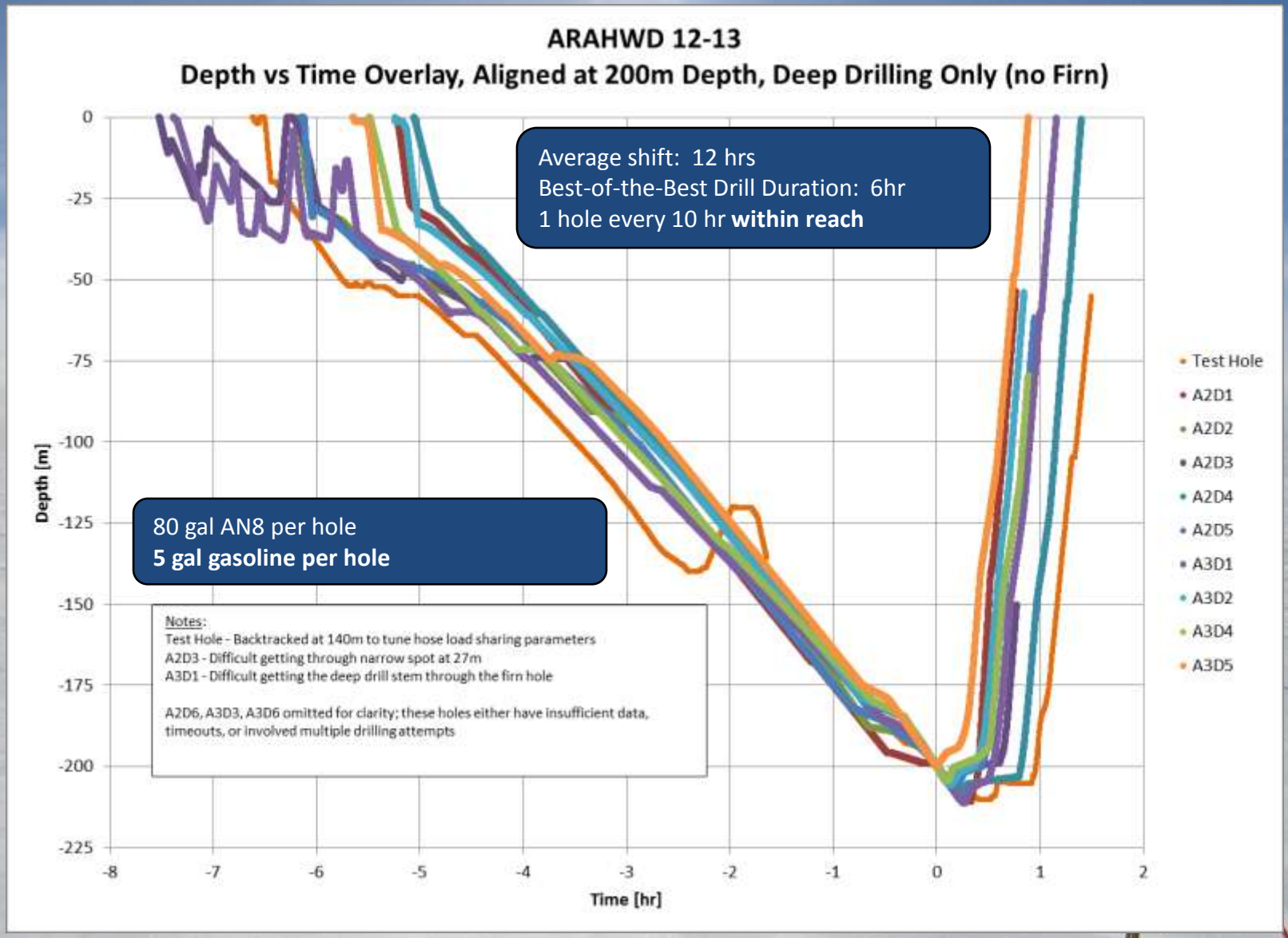
Challenges

- Freezeback 4x faster than IceCube
- Dry hole
- Reliability
- Portability

Takeaways

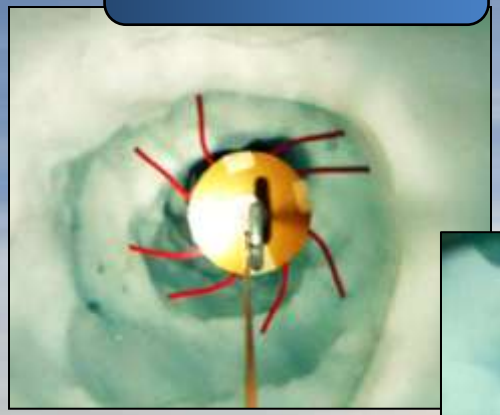
- New drilling technique
- Performance models and more hole modeling
- Video logging hole
- New discoveries about hole type
- Hose and cable bundle
- Load splitting hose reel and sheave without level winding
- Instrumentation
- Operations and Tools
- Staffing – RETAIN EXPERIENCE

ARA Hot Water Drill (ARAHWD) Performance



ARA Hot Water Drill (ARAHWD)
Performance – Hole Quality

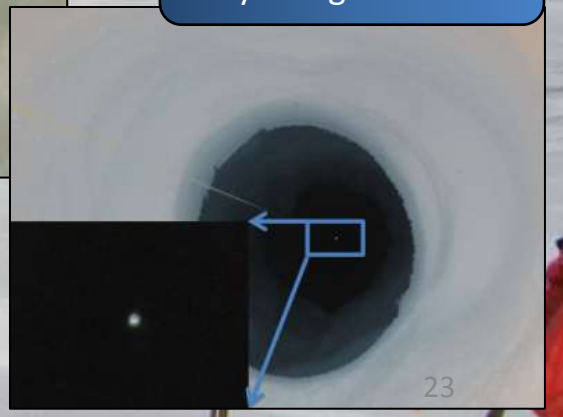
FIRN
0-40m



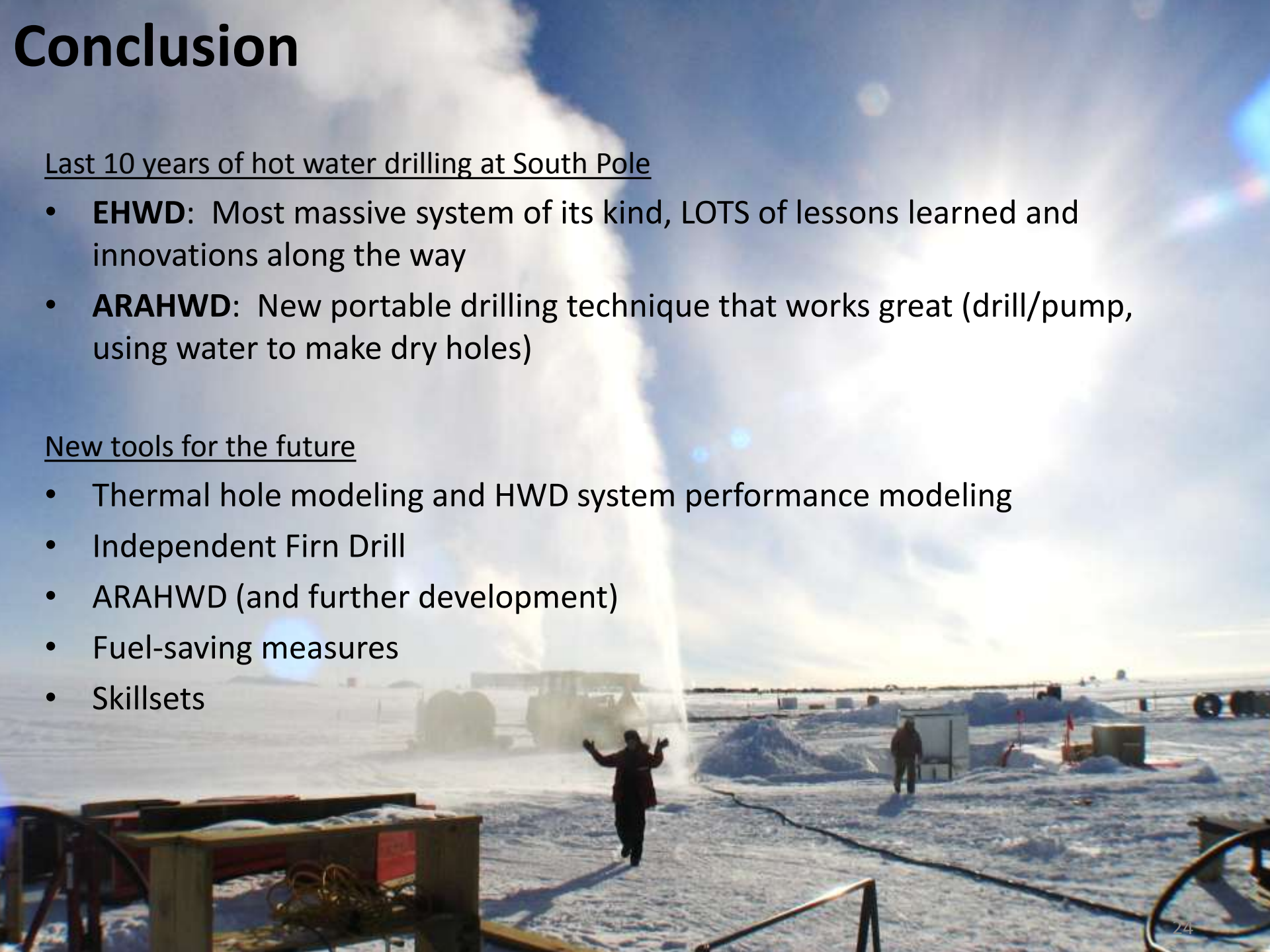
TRANSITION ZONE
40-120m

DEEP ICE
120-200m

STRAIGHTNESS
Very straight



Conclusion



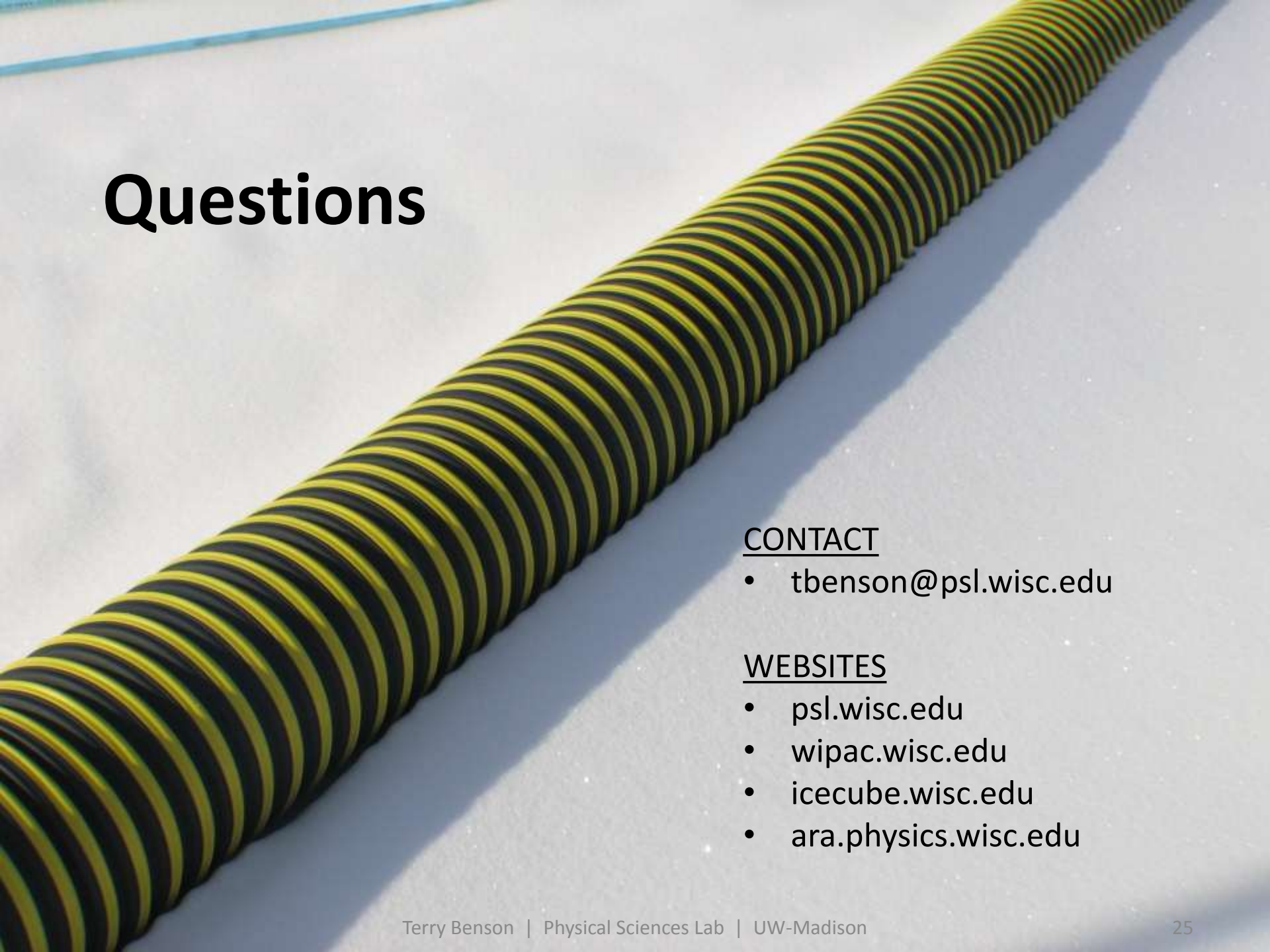
Last 10 years of hot water drilling at South Pole

- **EHWD**: Most massive system of its kind, LOTS of lessons learned and innovations along the way
- **ARAHWD**: New portable drilling technique that works great (drill/pump, using water to make dry holes)

New tools for the future

- Thermal hole modeling and HWD system performance modeling
- Independent Firn Drill
- ARAHWD (and further development)
- Fuel-saving measures
- Skillsets

Questions



CONTACT

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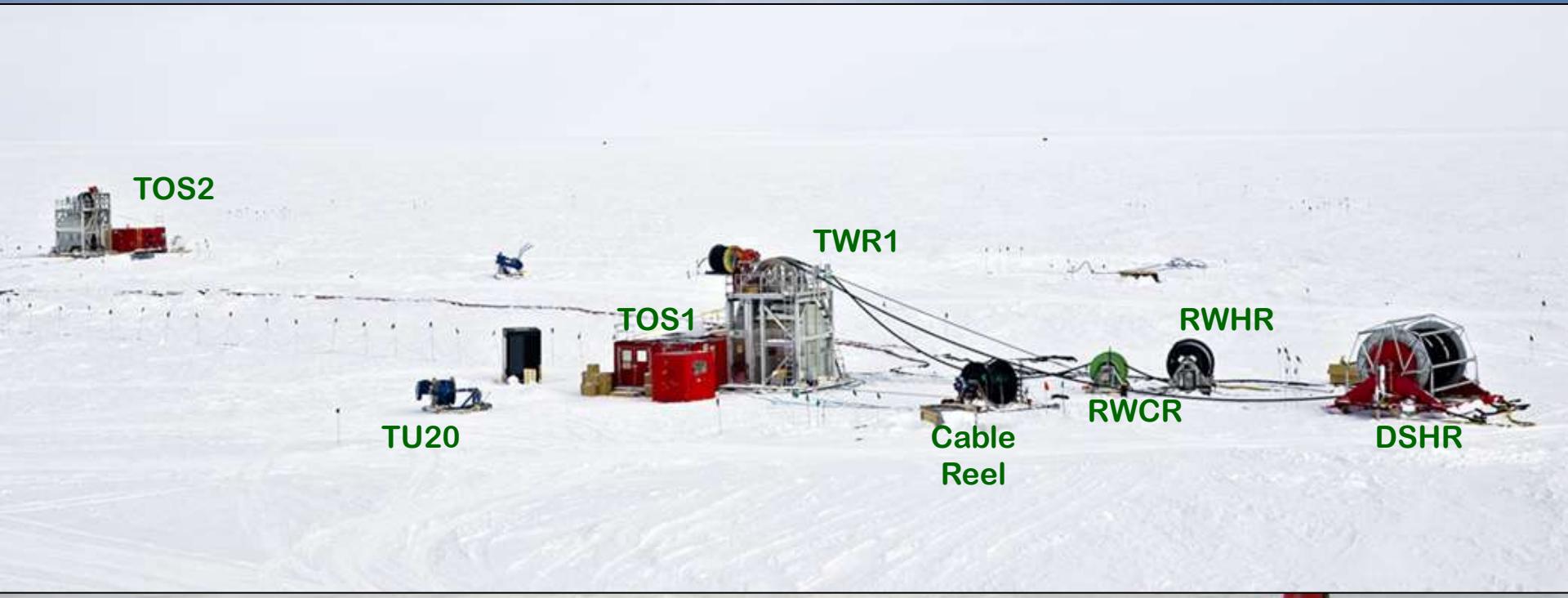
WEBSITES

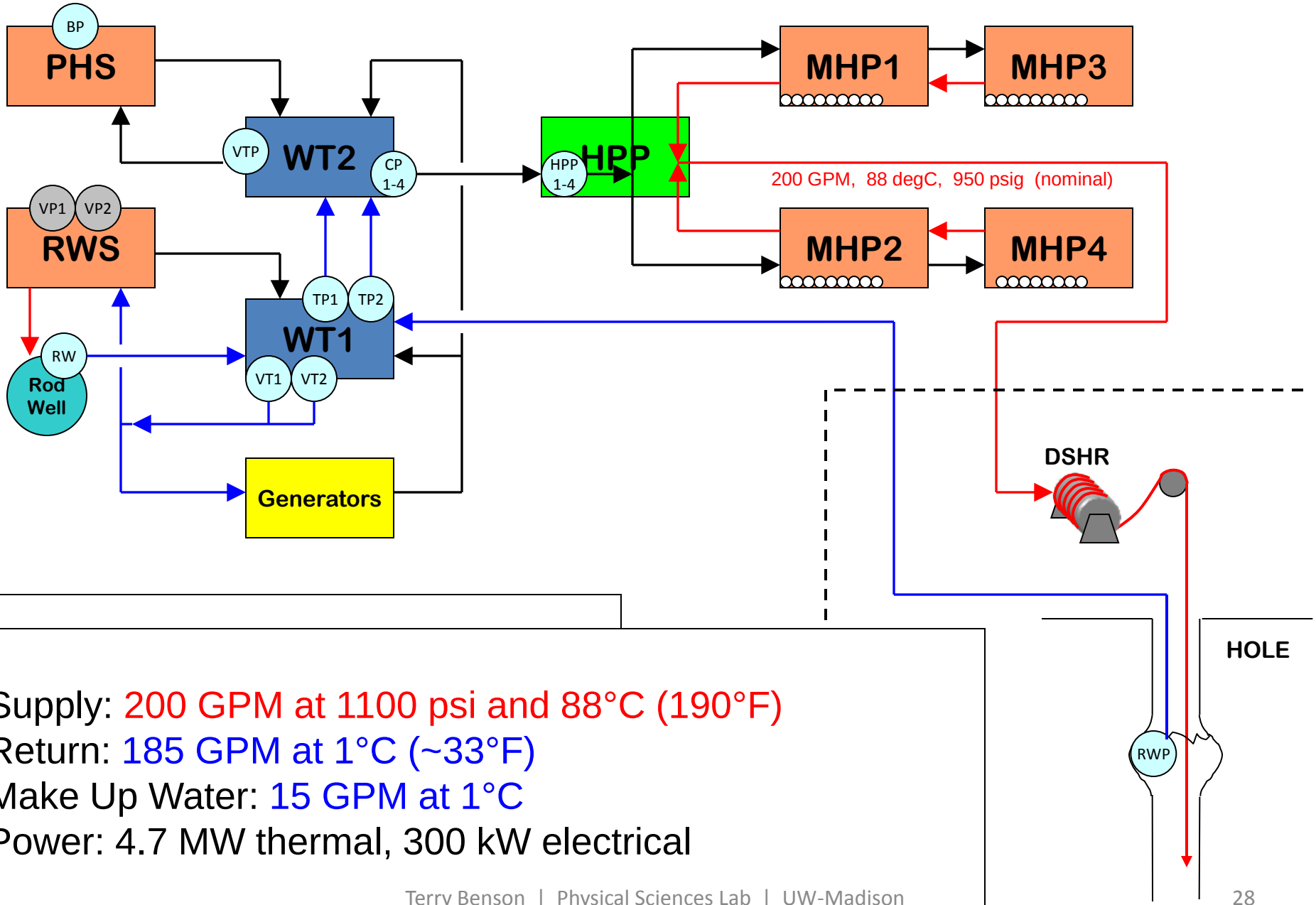
- psl.wisc.edu
- wipac.wisc.edu
- icecube.wisc.edu
- ara.physics.wisc.edu

EHWD Seasonal Equipment Site (SES, Drill Camp)

EHWD Tower Operations Site (TOS)



Enhanced Hot Water Drill Hydraulic Summary

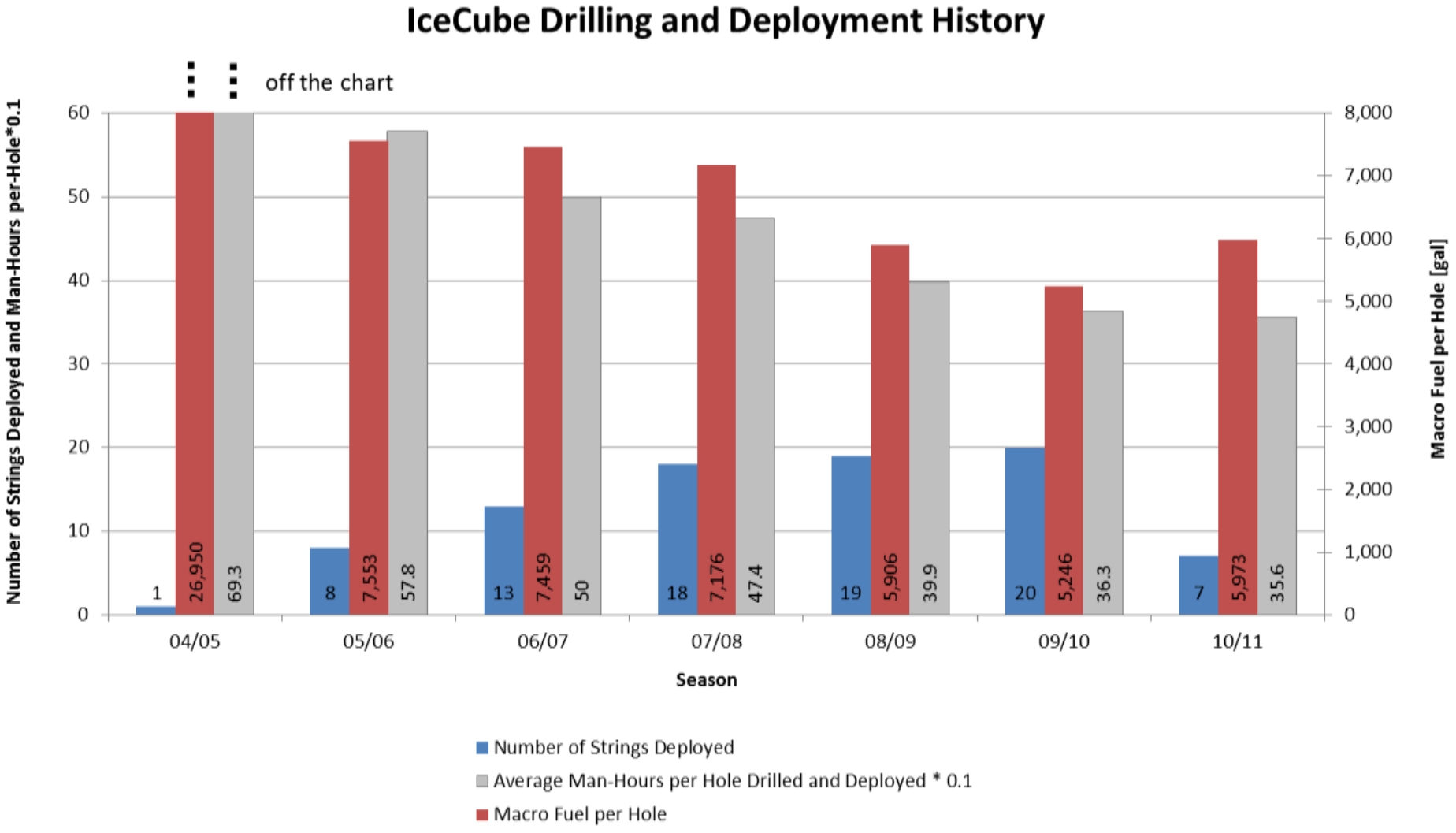


Supply: 200 GPM at 1100 psi and 88°C (190°F)
Return: 185 GPM at 1°C (~33°F)
Make Up Water: 15 GPM at 1°C
Power: 4.7 MW thermal, 300 kW electrical

EHWD System Specs

	Specification	Value	Unit	Comment
General	Total Power	5	MW	
	Thermal Power	4.7	MW	
	Electrical Power	300	kW	
	Weight	1.4 million	lb	total cargo est.
	Volume	120,000	ft^3	total cargo est.
	Max Drill Speed	2.1	m/min	oscillation limit
	Max Ream Speed	7.5	m/min	practical limit
	Flow	200	gpm	delivered to drill head
	Temperature	88	°C	delivered to drill head
	Pressure	1,100	psig	primary loop, at pumps
	Main Drill Hose ID	2.5	in	
	Length of Main Drill Hose on Reel	2,560	m	21 x 400 ft sections
Generators	Power Rating (sea level)	250	kW	each (3 total)
	Power Rating (10,000 ft)	165	kW	each (3 total)
	Heat Recovery (10,000 ft)	200	kW	each (3 total)
	Drill Power Consumption (drilling)	250	kW	electrical
	Drill Power Consumption (idle)	90	kW	electrical
Fuel	Burn Rate during Drilling	130	gph	
	Burn Rate during Idle	17	gph	
	Total Fuel per drill Hole (no firn drilling)	4,200	gal	approx. for 27-hour hole, experienced crew
	Total Fuel per Independent Firn Hole	300	gal	
	Base Fuel - Startup	8,000	gal/hole	includes Rodwell development
	Base Fuel - Idle	500	gal/hole	
	Daytank Capacity	300	gal	
Efficiencies	Overall System Efficiency	39	%	
	Main Heat Plant Efficiency	92	%	
	Drilling/Melting Efficiency	45	%	
Flows	Main Drill Flow	200	gpm	
	Return Water Flow	180	gpm	
	Makeup Water Flow	20	gpm	
	Idle Flow	30	gpm	
Times	Time to Drill/Ream a Hole	31	hr	27-hour hole
	Frequency of Holes	48	hr	experienced crew assumed
	Hole Lifetime Range	24-33	hr	historic, wider range is also available
Loads	Total Down-Hole Load at 2500 m	6,500	lb	
	Hose Tension Capacity	1,500	lb	limit until damage occurs
	Drill Cable Breaking Strength	20,000	lb	
	Tower Hoist Capacity	5,000	lb	
Nominal Hole	Diameter	60	cm	
	Depth	2,500	m	
	Volume of Ice	200,000	gal	

Enhanced Hot Water Drill (EHWD) Performance



ARA Station

ARA Hot Water Drill

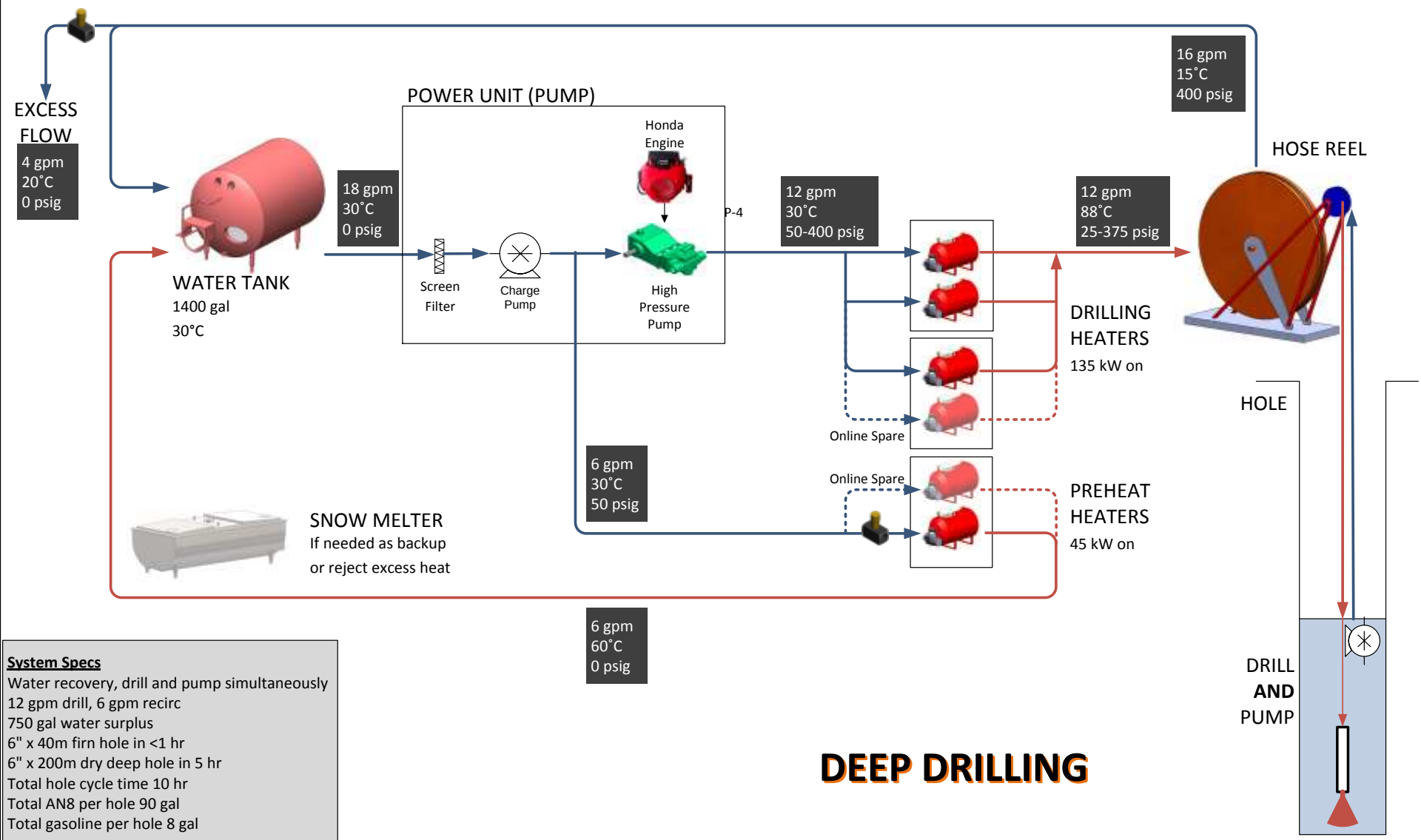
Generators

3k gal Fuel

MECC

ARA instrument deployment sled

-20°F outside
110°F inside!



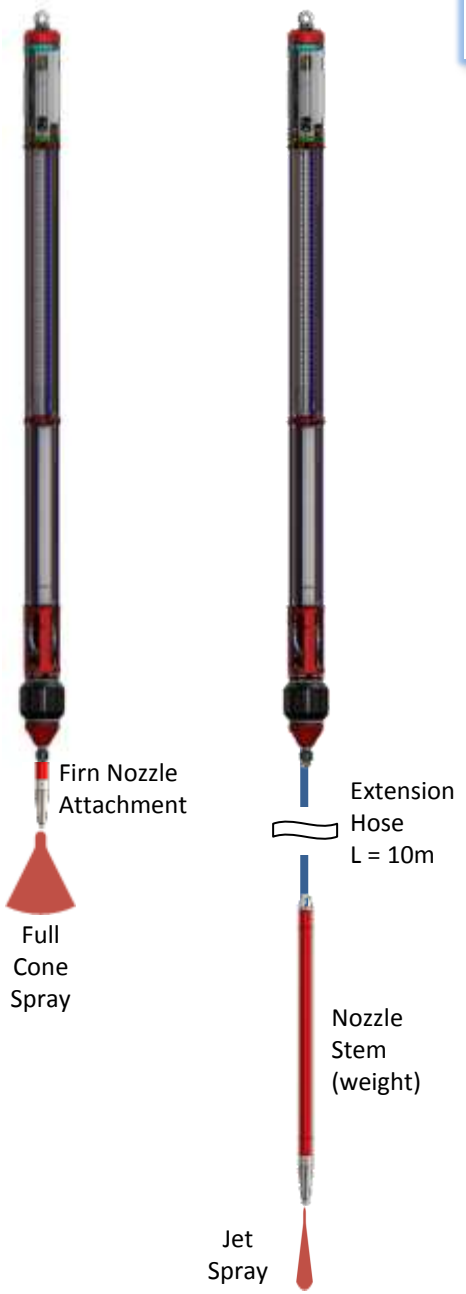
System Specs
Water recovery, drill and pump simultaneously
12 gpm drill, 6 gpm recirc
750 gal water surplus
6" x 40m firn hole in <1 hr
6" x 200m dry deep hole in 5 hr
Total hole cycle time 10 hr
Total AN8 per hole 90 gal
Total gasoline per hole 8 gal

DEEP DRILLING

ARA Drillhead Overview

FIRN Drilling

DEEP Drilling



ARA Hose Reel Overview

Hose and cable bundle

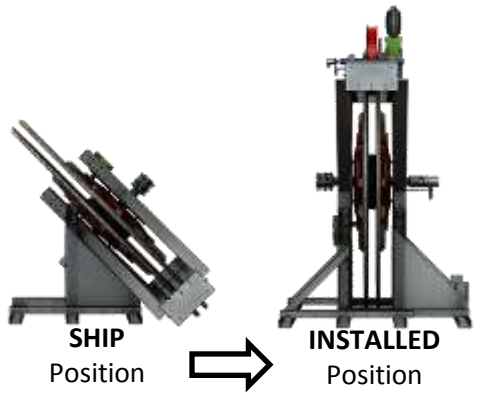
- 2x hoses and 1x combo cable
- Multi-reel joined at hole not a solution
  - Load to be shared amongst all 3 members, intricate syncing control would be required
  - Extra task at hole of joining/separating members
- Manufactured umbilical with round cross-section too expensive, too big
- Decided to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

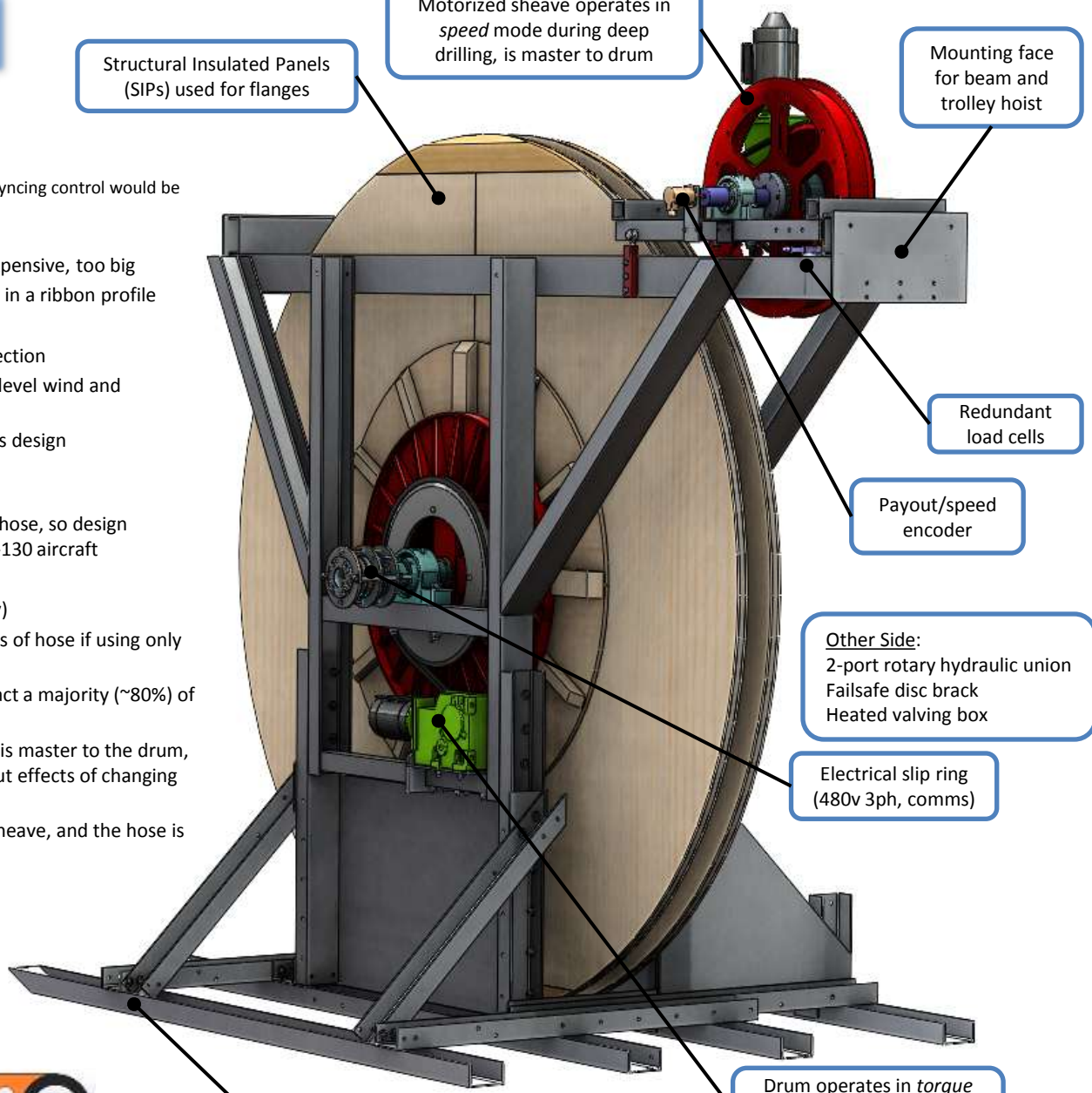
- A dry hole results in high down-hole loads (no bouyancy)
- High loads + many layers would collapse the lower layers of hose if using only the drum to react the load
- Motorized sheave utilizes friction with the bundle to react a majority (~80%) of the down-hole load, like a capstan winch
- In this 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

Bundle X-section



ARA HOT WATER DRILL SPECS			
Type	Hot water drill		
Configuration	Towable 3-sled train		
Tow Vehicle	CAT 953 or equivalent for short moves D6 or equivalent for long moves Packed roads and pads required		
Nominal Hole Dia	16-20 cm (6-8 in)		
Max Hole Depth	210 m		
Capabilities	Water-filled (traditional) hole Dry hole (drill/pump simultaneous) Closed-circuit firn drilling (requires upgrade) Off-site drilling with backup generator Snow melting, if required		
Capacities	300 kW thermal 22 gpm total flow 12 gpm nominal drill flow 6-8 gpm excess water (using drill/pump simultaneous method) 1000 psi max system pressure 1700 lb max total down-hole load 1400 gal insulated water storage 240 gal online AN8 fuel tank 120 gal online glycol tank 30 kW (sea level) backup generator, 480VAC 3-phase		
Elec Power Consumption	24 kW steady state 33 kW peak (est.) 480VAC 3-phase 60-amp connection in		
Crew Size	5		
Auxiliary Equipment	Generators Reserve online water tank Reserve glycol and gasoline barrels NHG heater and wind breaks MECC (warm space for breaks, meals, and meetings)		
Target Hole Peformance			
Hole Specs	16 cm (6 in) diameter x 200 m DRY, @ South Pole		
Drill Time	7 hours		
Cycle Time	10 hours		
AN8 Fuel	78 gal		
Gasoline	5 gal		
Sled-by-Sled	**Sled 1**	**Sled 2**	**Sled 3**
Function	Power distribution, backup gen, storage	Water storage and pumping	Water heating, snow melting, control, and hole ops
Weight EST., dry (wet)	11,000 lb (11,000 lb)	8,000 lb (20,000 lb)	15,000 lb (18,000 lb)
Footprint, L x W	16 ft x 8.5 ft w/o tongue Tongue adds approx 10 ft to length	16 ft x 8.5 ft w/o tongue Tongue adds approx 10 ft to length	20 ft x 7.75 ft w/o tongue Tongue adds approx 10 ft to length
Comments	Hose reel collapses into 45° shipping position to allow transport via LC-130 aircraft (also must be removed from sled)		

Challenges at South Pole

- Antarctica: The coldest, windiest, and driest place on earth
- Station “open” during short austral summer, Oct-Feb
- Average Annual Temp is -49°C
- Average Summer Temp is -33°C
- Winter Temps to -80°C
- World’s largest desert, DRY
- Altitude is ~10,000 ft
- Isolated

Hot Water Drill Design Template

- Define hole size and quantity
- How fast do they need to be drilled?

✓ **Required thermal power**

- Upper water temperature limit is boiling (South Pole: 88°C)

✓ **Required flow**

- Find the right hose
- Maximize pressure -> Maximize nozzle velocity -> Maximize drill speed

✓ **Pump, heater, tank sizing, etc.**

✓ **Requirements + Budget + Time = Component Selection**