IceCube's

Enhanced Hot Water Drill

Terry Benson

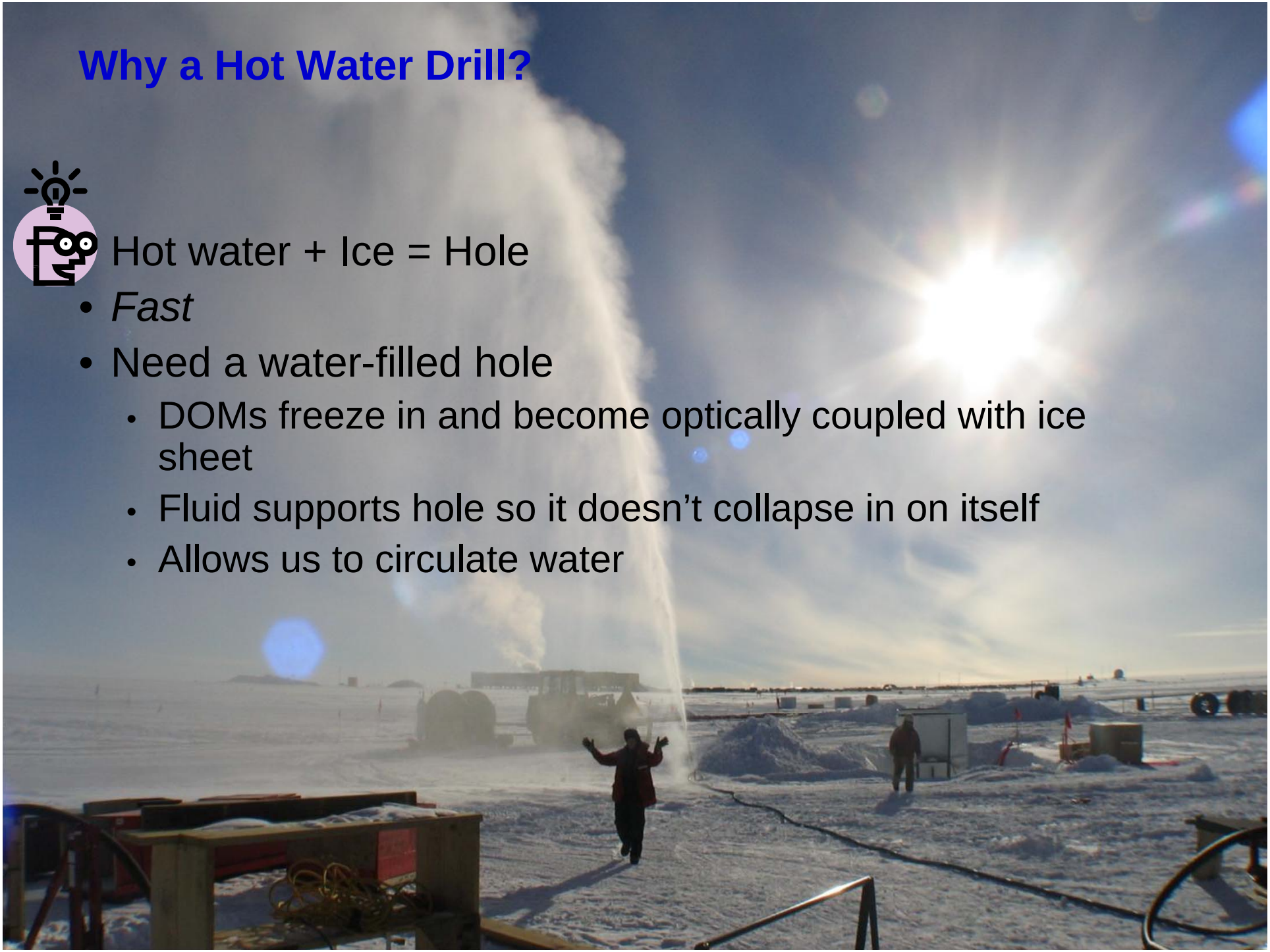
IceCube

Antarctic Science Symposium | Innovations in Hot Water Drilling | April 27 | Madison

Talk Summary

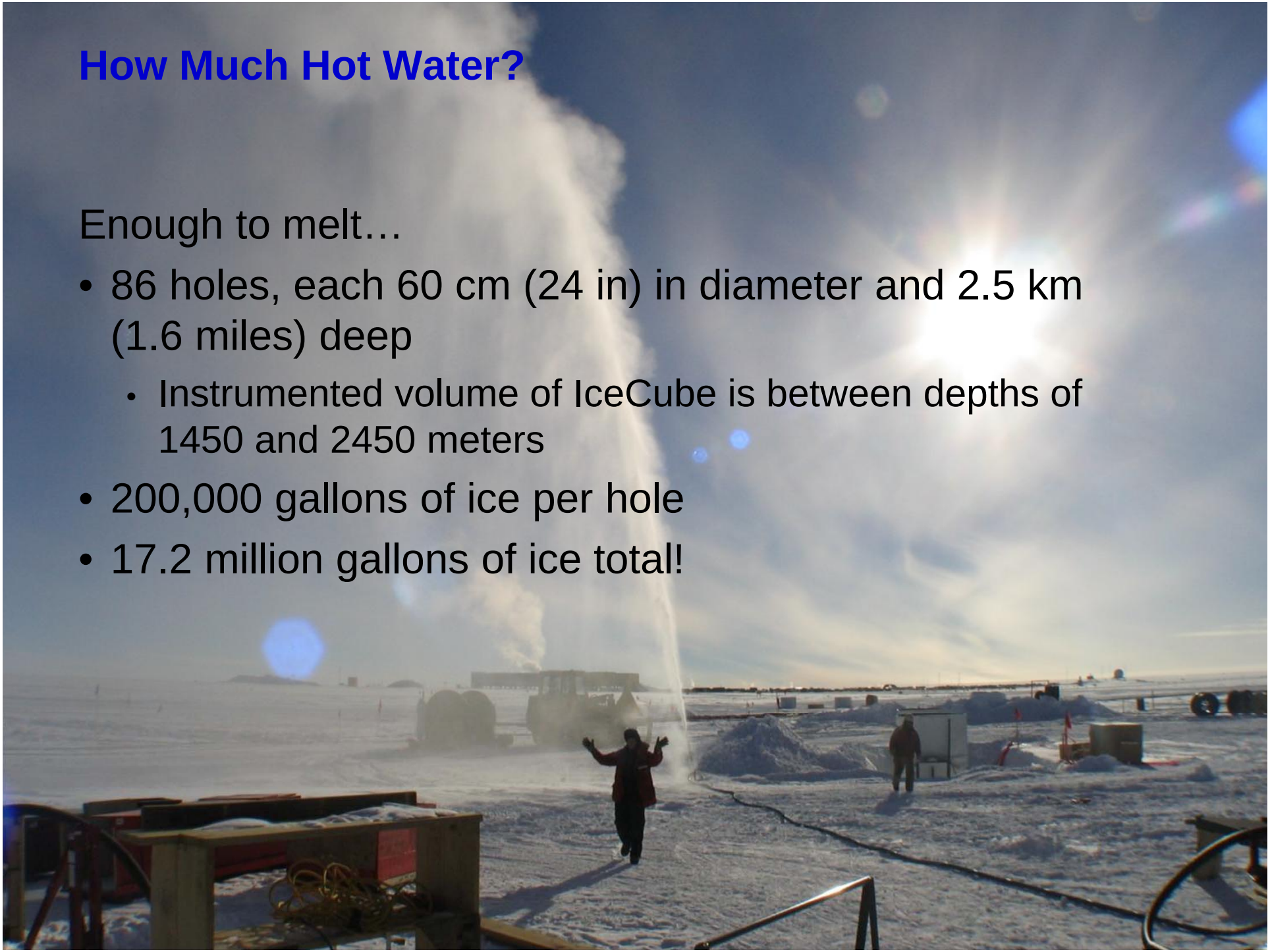
- **Enhanced Hot Water Drill (EHWD) Purpose and Philosophy**
- **System Overview**
- **Performance**
- **Lessons Learned**

Why a Hot Water Drill?



- 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

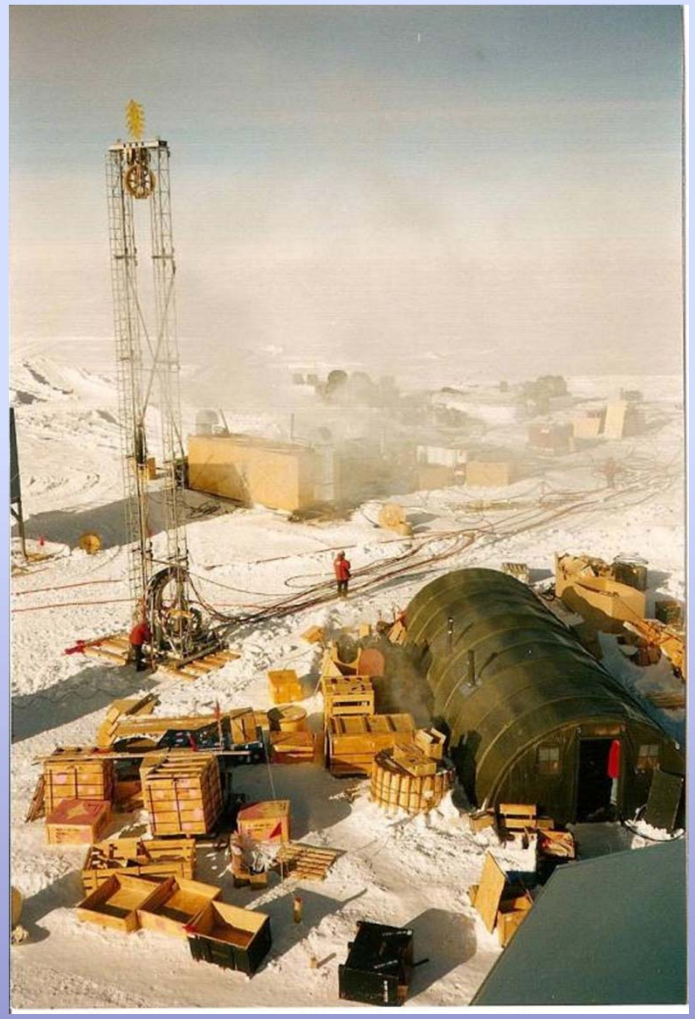
How Much Hot Water?



Enough to melt…

- 86 holes, each 60 cm (24 in) in diameter and 2.5 km (1.6 miles) deep
  - Instrumented volume of IceCube is between depths of 1450 and 2450 meters
- 200,000 gallons of ice per hole
- 17.2 million gallons of ice total!

The Amanda Days
(IceCube's proof-of-concept)

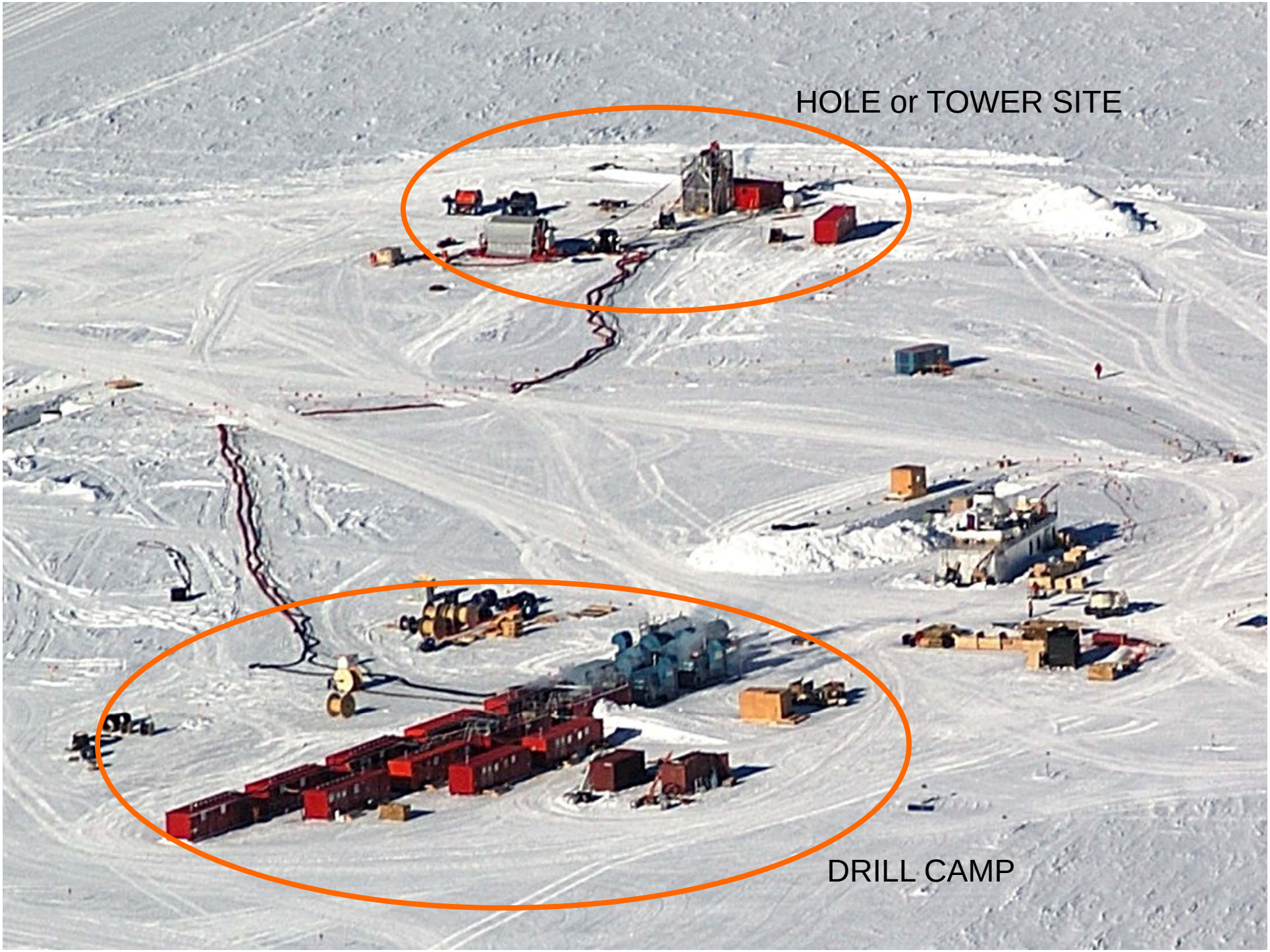


WATER RESERVOIR → PUMP → HEAT → SHOOT OUT NOZZLE → RECIRCULATE

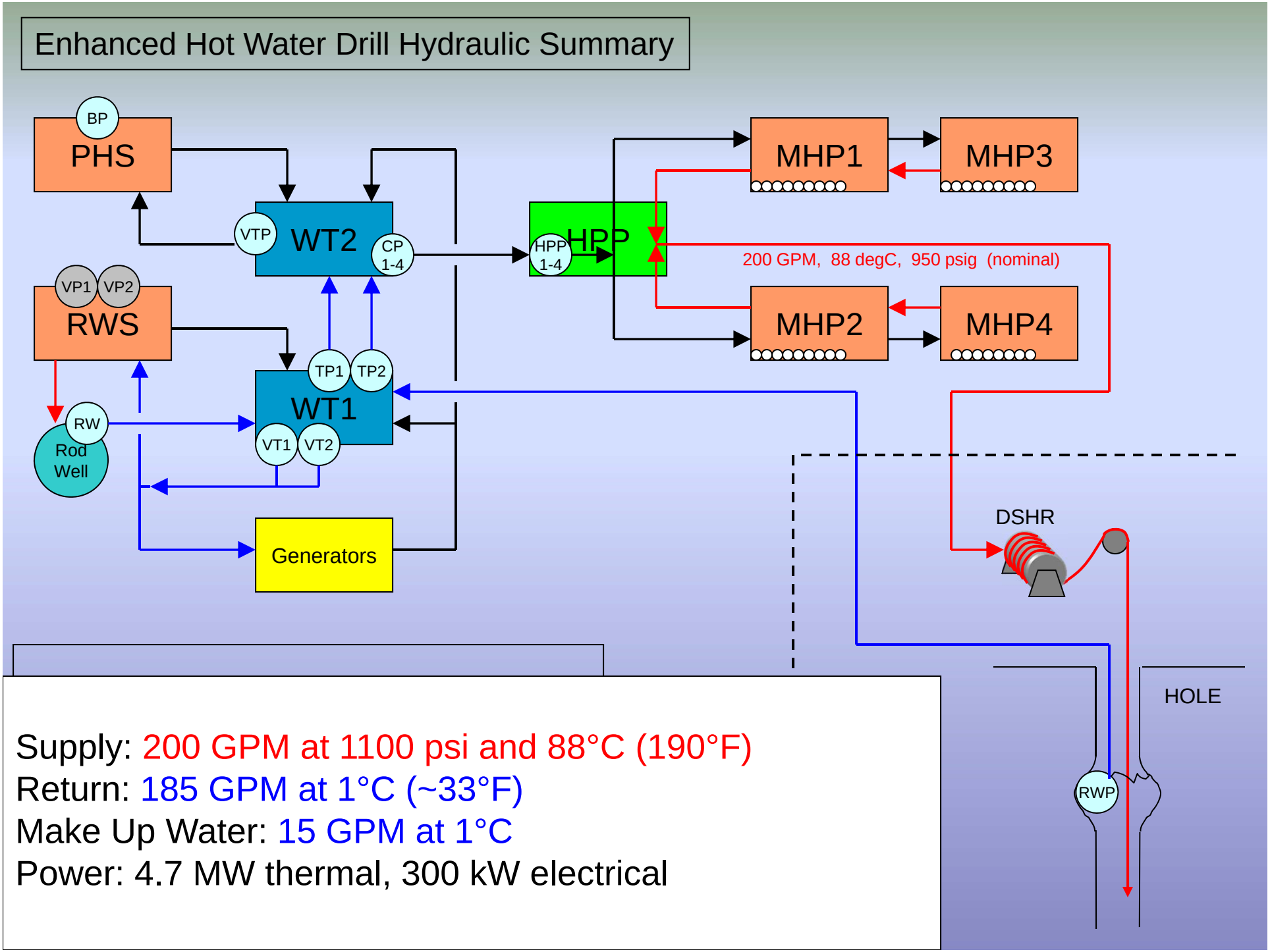
IceCube – the *Enhanced* Hot Water Drill

- Leverage Amanda Experience
  - Use the same equipment where it worked
  - People with experience
- Major Improvements
  - Double thermal power (100 GPM -> 200 GPM)
  - One “piece” drill hose – big hose reel
  - Automated control, AutoDrill
  - Two drilling structures
  - Modular design - packed in shipping containers
  - Independent Firn Drill
- Fuel Efficiency is a design driver
  - More power = Faster Drilling = Less Fuel
  - High Efficiency Heaters
  - Drilling Strategy

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

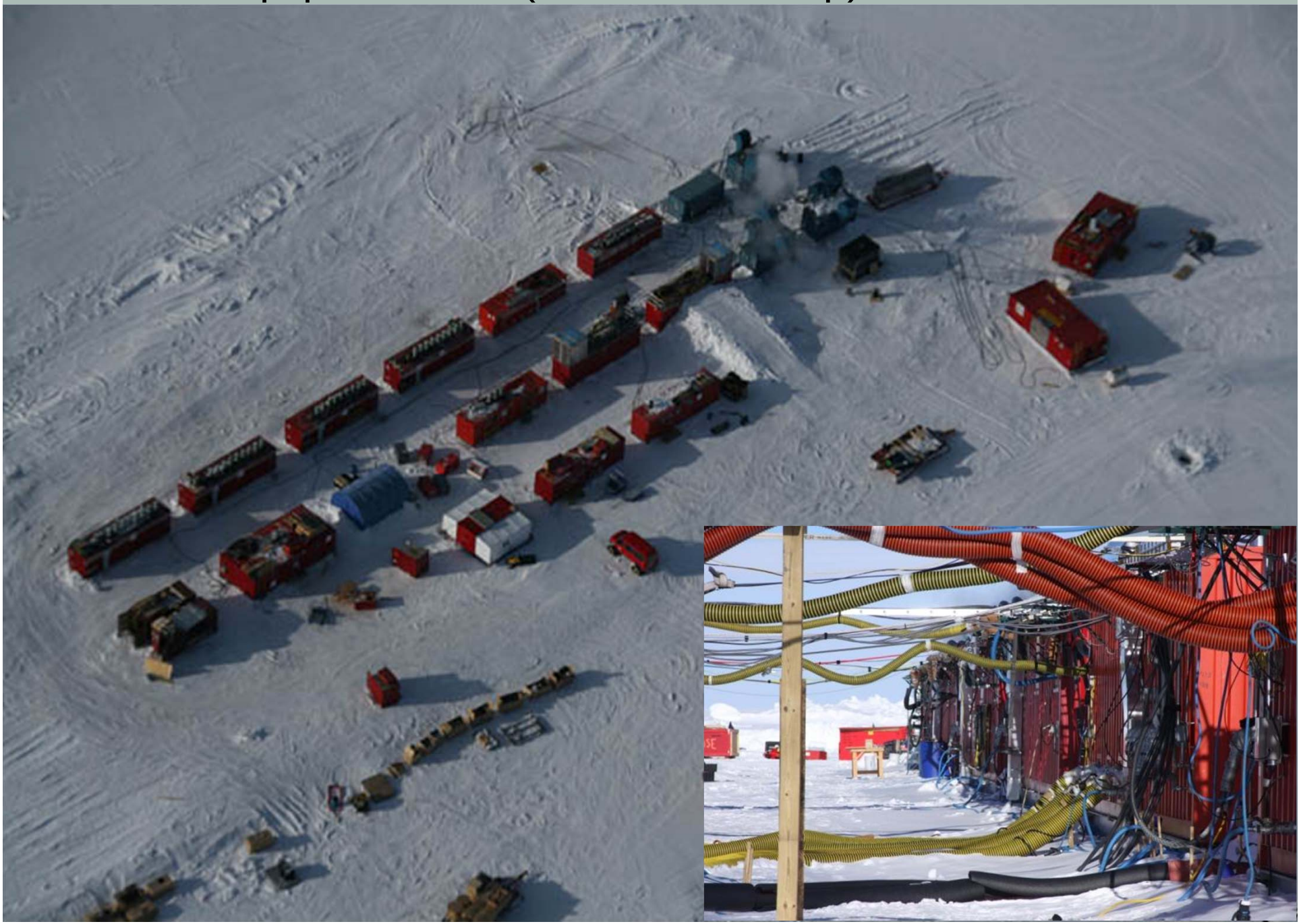

HOLE or TOWER SITE
DRILL CAMP

Enhanced Hot Water Drill Hydraulic Summary



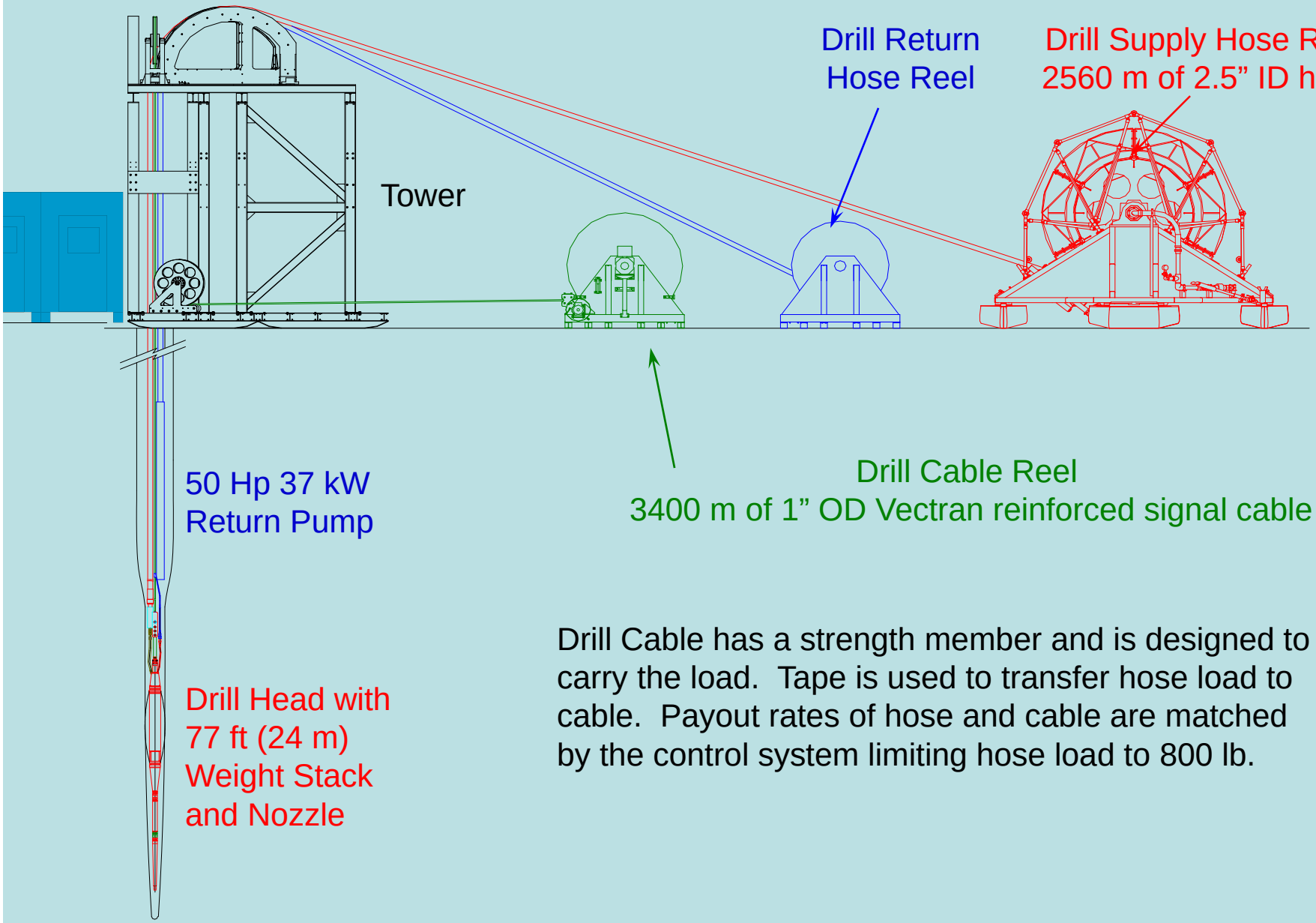
Supply: 200 GPM at 1100 psi and 88°C (190°F)
Return: 185 GPM at 1°C (~33°F)
Make Up Water: 15 GPM at 1°C
Power: 4.7 MW thermal, 300 kW electrical

Seasonal Equipment Site (SES, Drill Camp)



Tower Operations Site – TOS Delivers Water to Hole

Deep Drilling Illustration

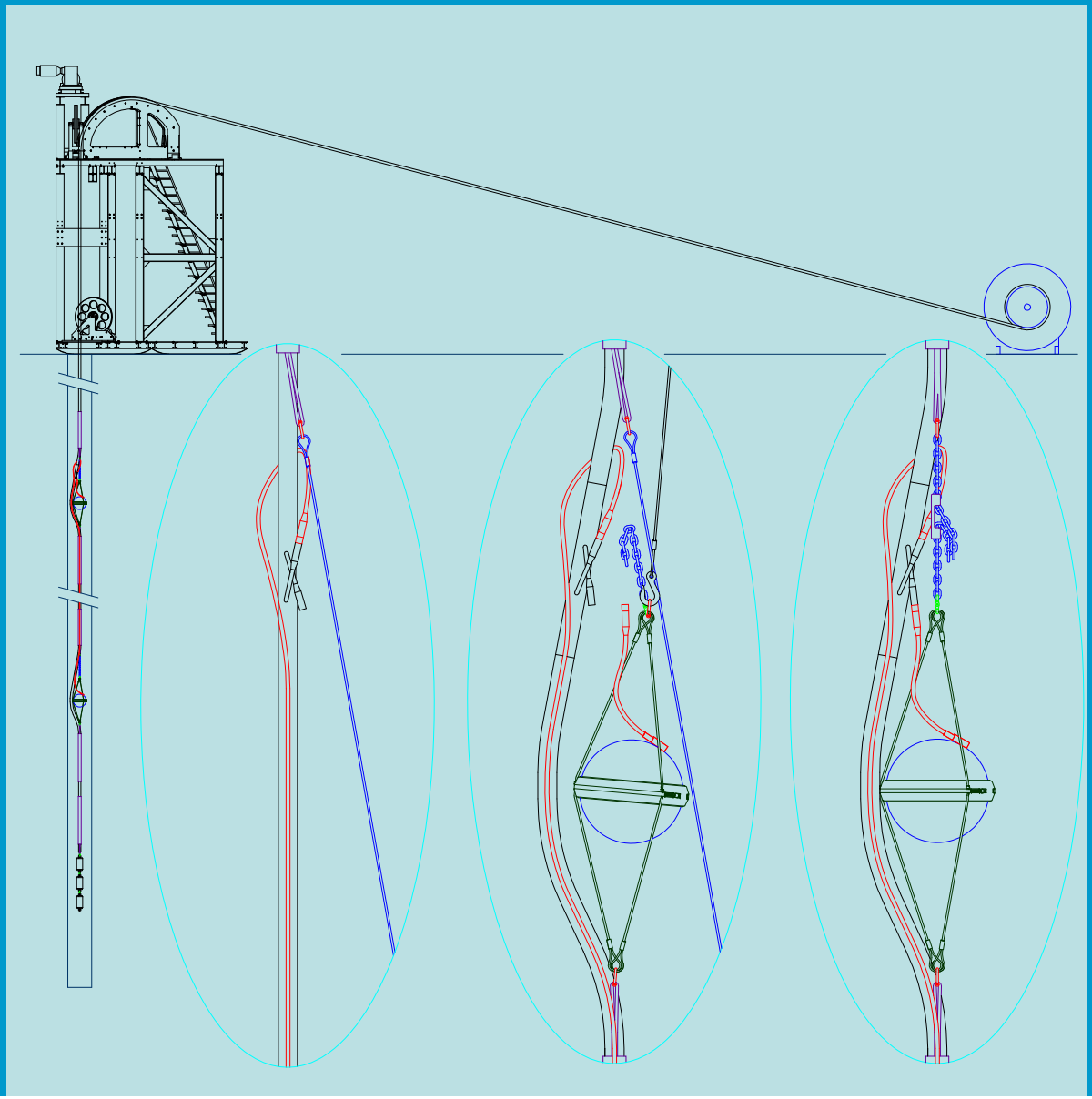


Drill Cable has a strength member and is designed to carry the load. Tape is used to transfer hose load to cable. Payout rates of hose and cable are matched by the control system limiting hose load to 800 lb.

Deployment of DOMs

String cable 2500 m - Weight ~6 tons

Deployment Illustration



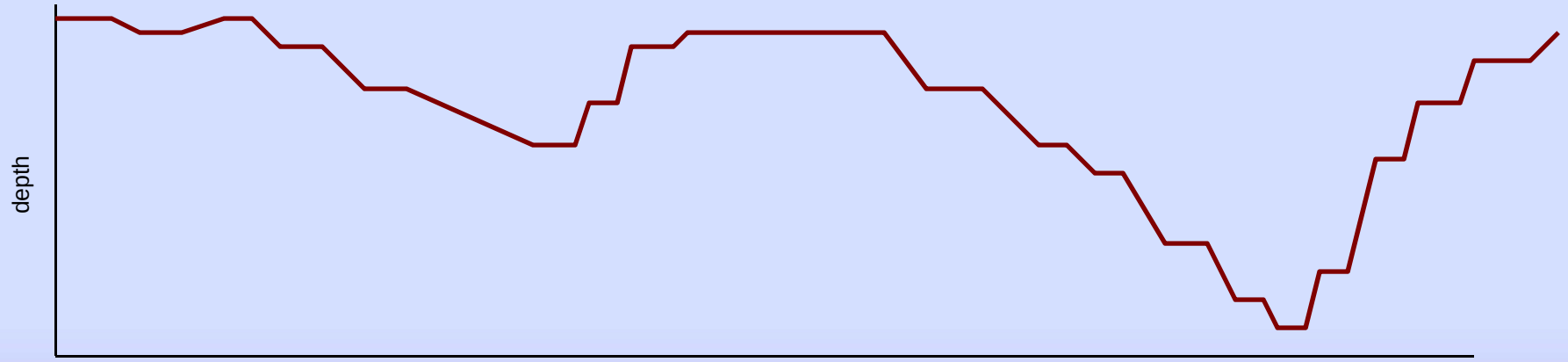
	Specification	Value	Unit	Comment
General	**Total Power**	**5**	**MW**	
	Thermal Power	**4.7**	**MW**	
	Electrical Power	**300**	**kW**	
	Weight	**1.4 million**	**lb**	**total cargo est.**
	Volume	**120,000**	**ft^3**	**total cargo est.**
	Max Drill Speed	**2.1**	**m/min**	**oscillation limit**
	Max Ream 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	**200**	**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 Working Load	10,000	lb	
	Tower Hoist Capacity	5,000	lb	
Nominal Hole	Diameter	60	cm	
	Depth	2,500	m	
	Volume of Ice	200,000	gal	

How Did It Do?

- 86 holes in 7 field seasons
- Drilled 20 holes in a season (09/10)
- Demonstrated deep drilling in 27 hours (average 31 hours)
- Demonstrated hole-to-hole frequency of 32 hours (average 48 hours)
- Demonstrated deep drilling of a hole with 3850 gallons of fuel, including firn drilling (average 4400 gallons)
- Reliability of drill has become very good
- Drilling models have good agreement with actual performance
- Staffing
  - 3 shifts, 9 hours, 9 people
  - Drill runs 24/7, no less than 2 person skeleton crew on days off
  - Experts spread throughout shifts (electronics, software, heaters, etc.)
  - Retaining experience is the most critical component of success

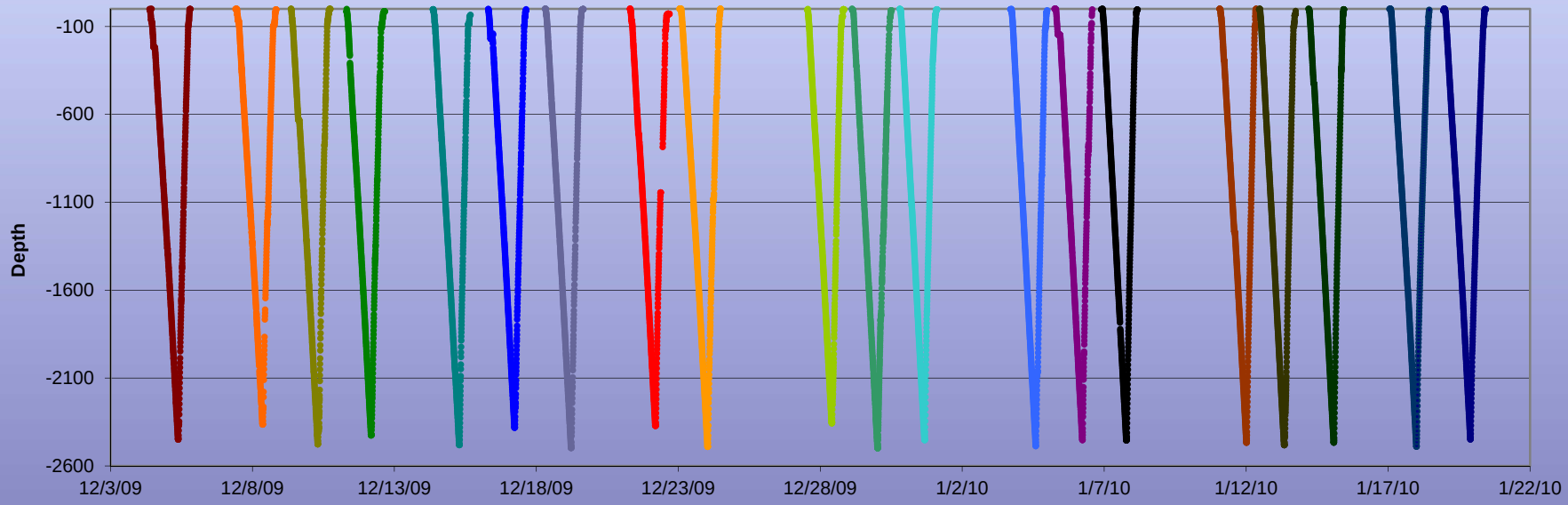
How Did It Do?

2004-2005: 1 (and a half) holes

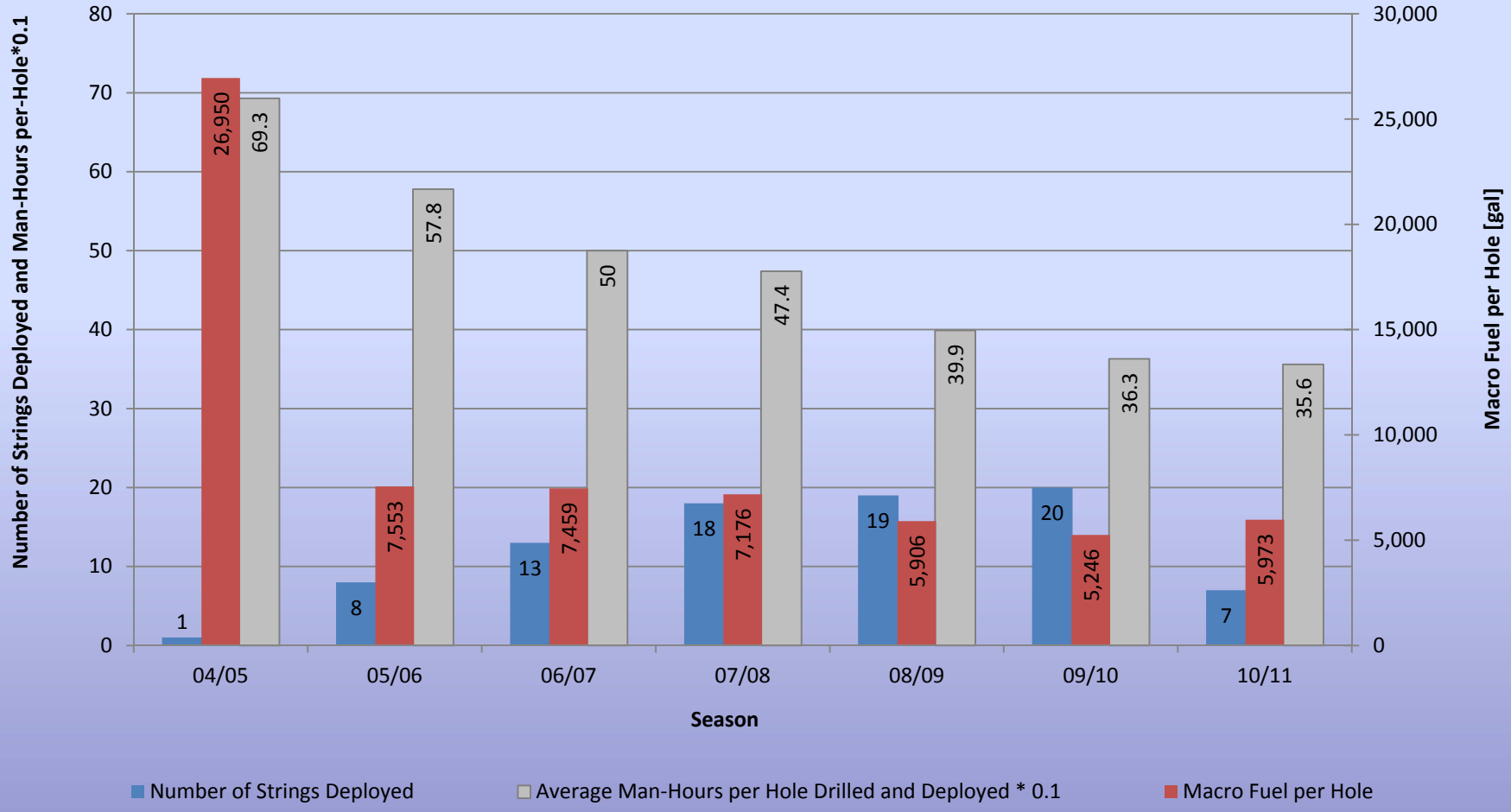


Drilling Over Course of Season

2009-2010: 20 holes



IceCube Drilling and Deployment History



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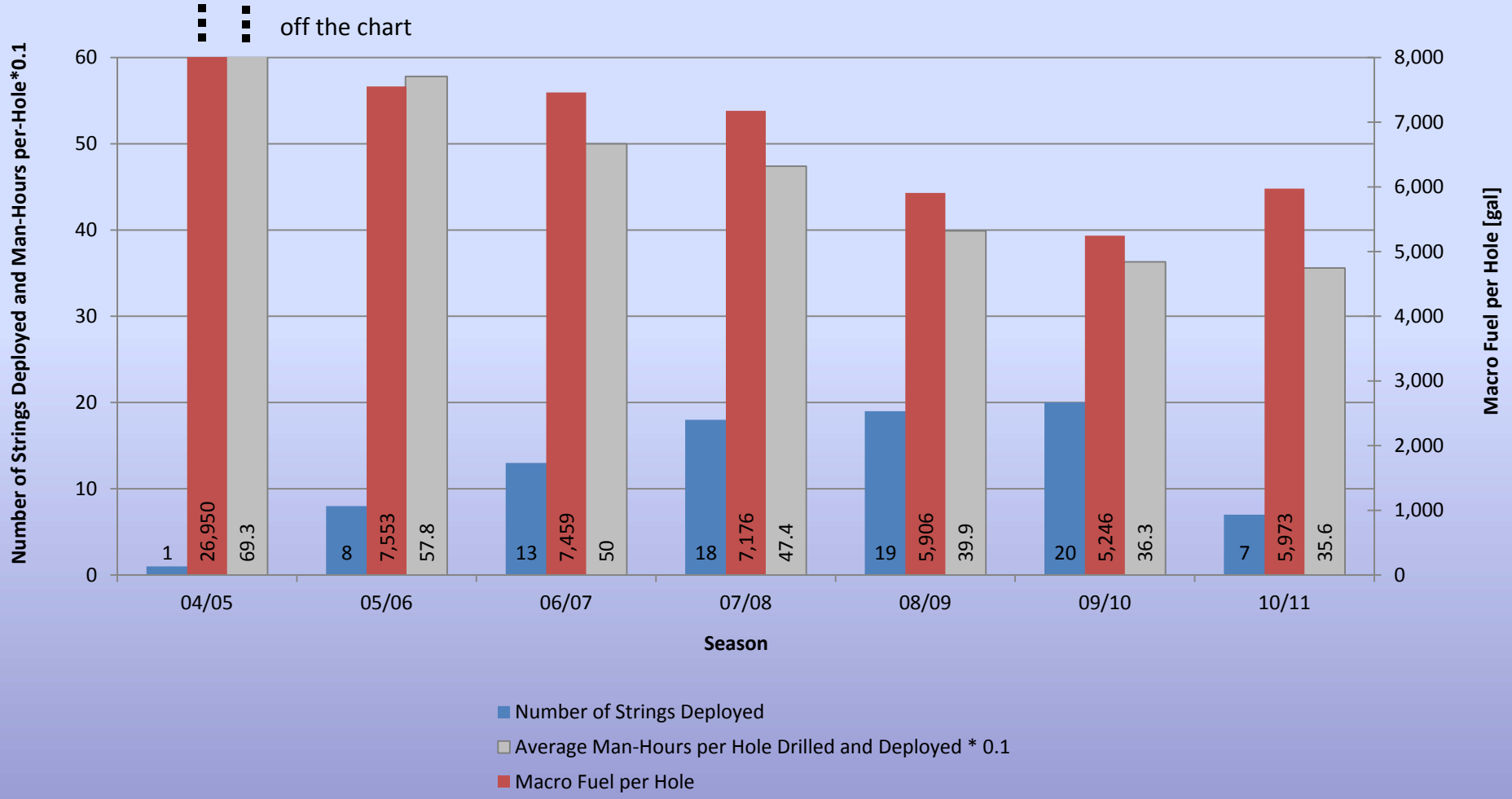
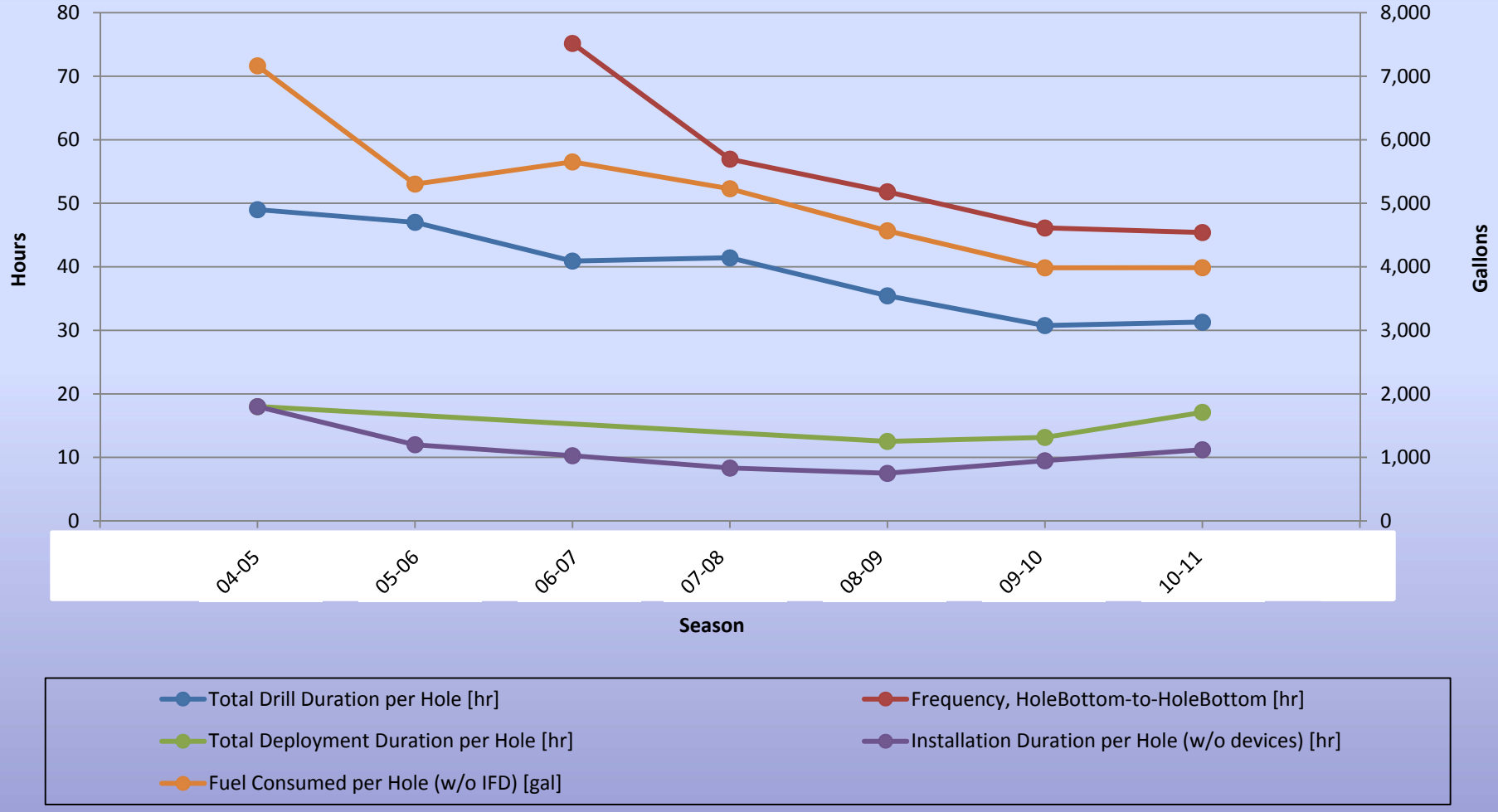


SEASON-TO-SEASON AVERAGES



Some Lessons Learned

- Hole modeling and freeze back tools
- Hose and its challenges
- Nozzle velocity very important
- Independent Firn Drill
- Generator heat recovery
- Heater efficiency and safeties
- Heated hose
- Rodwell strategies and fuel saving measures
- Staffing – retain experience!

Questions?

Backup Slides

Hot Water Drill Design Template

- Define required hole characteristics (how big, how many?)
- How fast do they need to be drilled?

✓Required thermal power

- Upper limit on water temp at S. Pole is 88 C (boil pt.)

✓Required flow

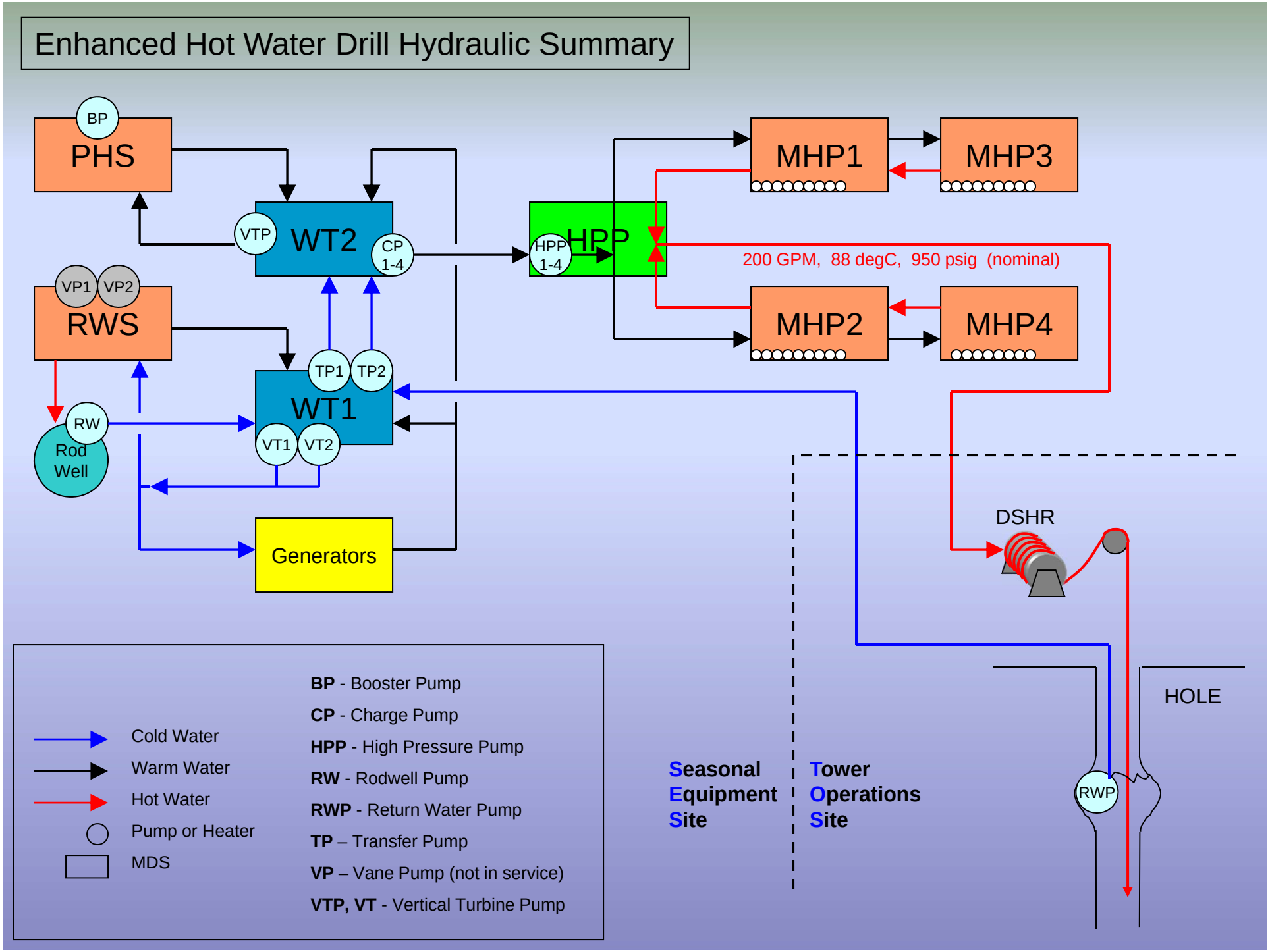
- Find the right hose
- Maximize system pressure -> Maximize nozzle velocity -> Maximize drill speed

✓Pump sizing, heater sizing, tank sizing, etc.

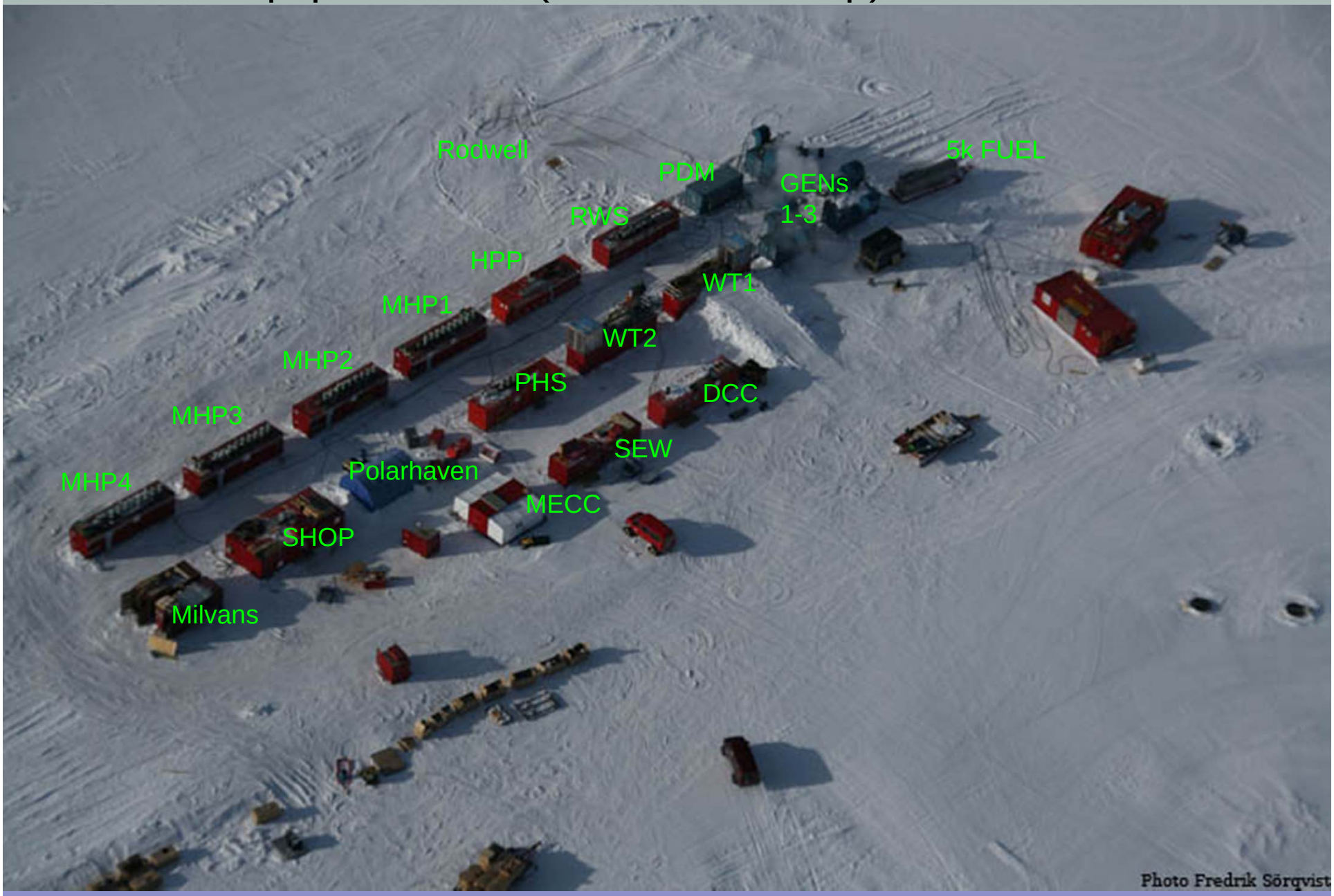
✓System specs + budget + time = Component selection

* In the case of the EHWD, fuel efficiency was one of the biggest design drivers

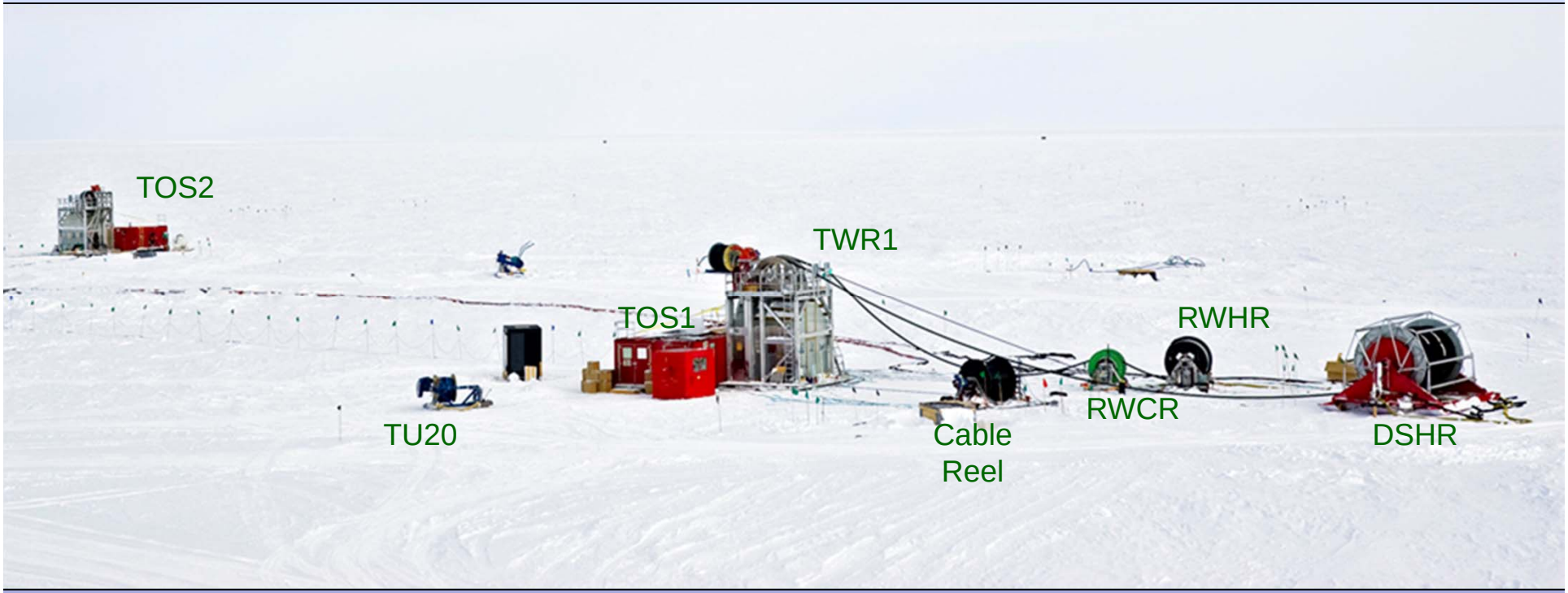
Enhanced Hot Water Drill Hydraulic Summary



Seasonal Equipment Site (SES, Drill Camp)

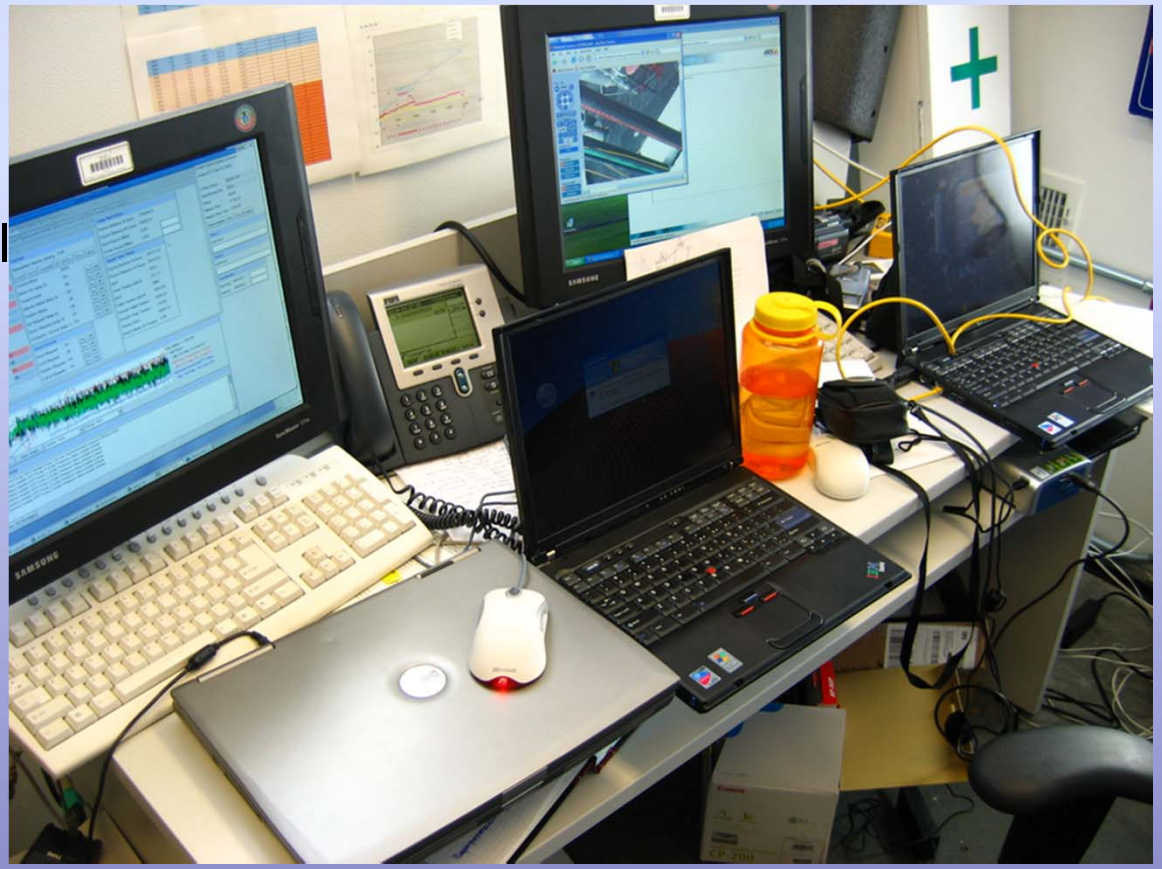


Tower Operations Site (TOS)



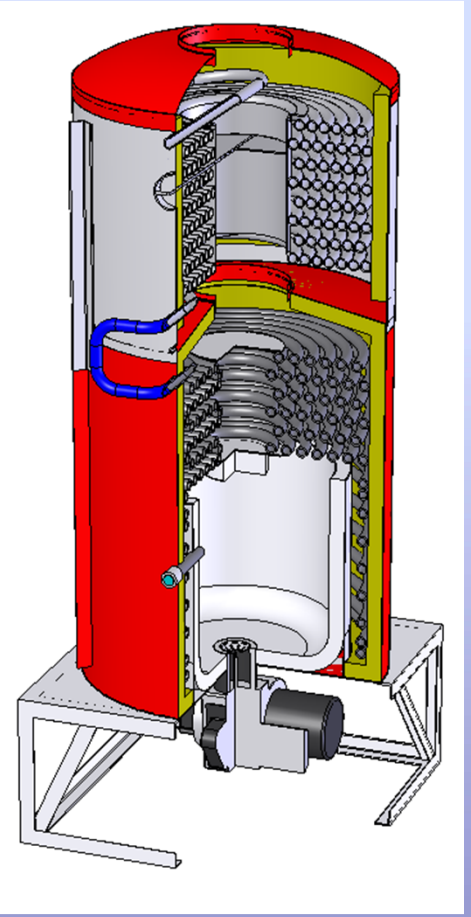
Some Notables – Control System

- Advanced computer control system
- Monitor flows, temps, pressures, environmental conditions, equipment performance
- Except for some manual valves, most everything in the system can be controlled from the control system computers
- AutoDrill controls drill and ream speed based on system variables



Some Notables – High Efficiency Water Heaters

- Fuel-fired (~3.5 GPH of JP8)
- Heating capacity: ~125 kW (0.43 MBtu/hr)
- High pressure (1000 psig)
- Re-designed for high fuel efficiency
  - Improved off-the-shelf heater from 78% efficiency (LHV) to 93% efficiency (HHV)!
  - Added upper condensing heat exchanger
  - Added molded ceramic combustion chamber
  - Combustion temp: 1120°C (2048°F)
  - Stack temp: 45°C (113°F)
- The drill has 39 of these heaters



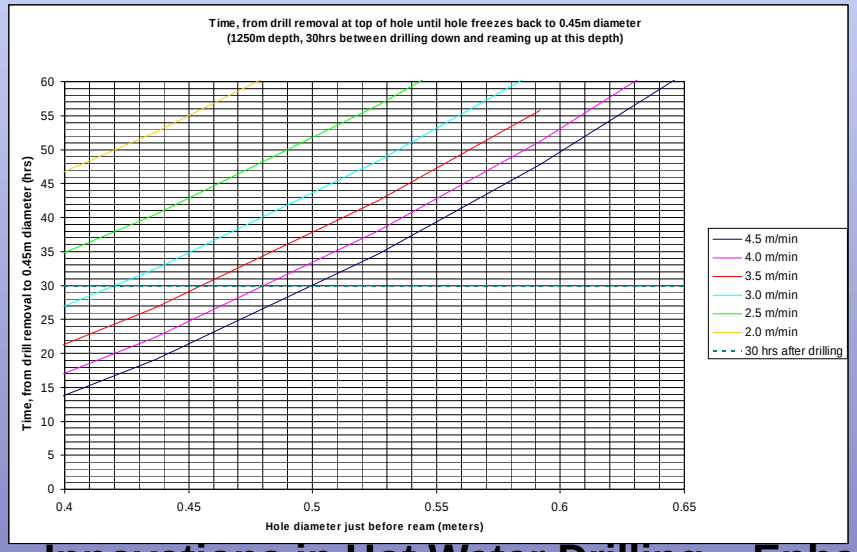

M H P 3

Some Notables – Drillhead

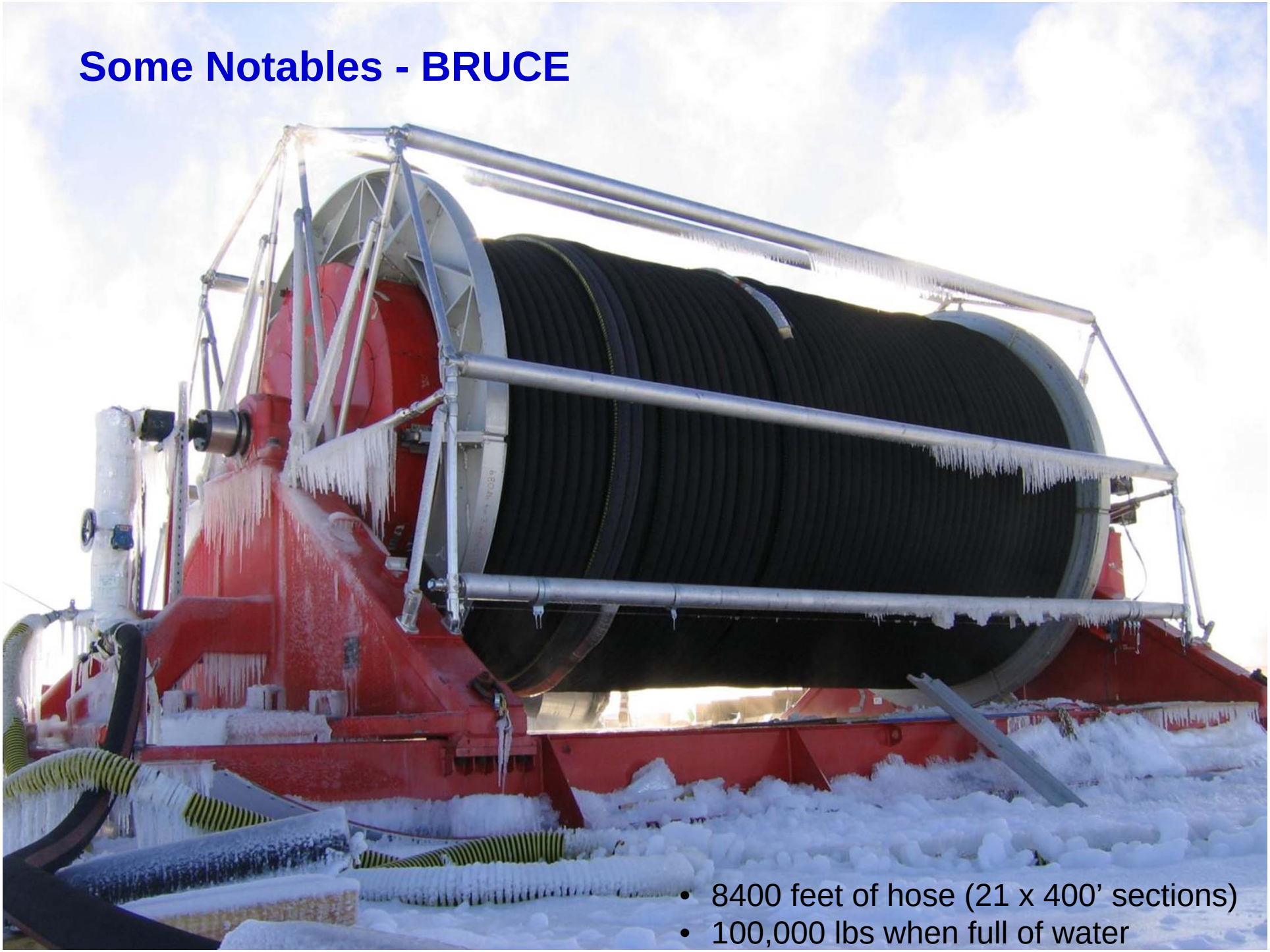
- Provides valuable feedback
- Nav pack
- Calipers for reading hole diameter
- Temp and pressure for both drill water and hole water
- 78 foot weightstack hangs off bottom of drillhead, with ¾” nozzle at end

Some Notables – Hole Modeling and Drilling Strategy

- Detailed models developed to understand the dynamics of drilling into ice
- Drilling and reaming speeds optimized to get the perfect-sized hole using minimal fuel
- Faster speeds for shorter hole lifetimes



Some Notables - BRUCE



- 8400 feet of hose (21 x 400’ sections)
- 100,000 lbs when full of water

Drilling & Deployment Tasks

- Independent Firn Drill to 50 m
- Prehole check list
- Deep Drill to 2450 m from 1.5 to 2.2 m/min
- Ream hole to size (60 cm +/-) from 2 to 5 m/min
- Acceptance of hole
- Caliper Logging or Dust Logging of Hole
- Setup deployment winch (TU-20)
- Deploy DOMs and cable
- Special Device Installation
- Acceptance of string
- Move TOS to next hole

IceCube Drilling

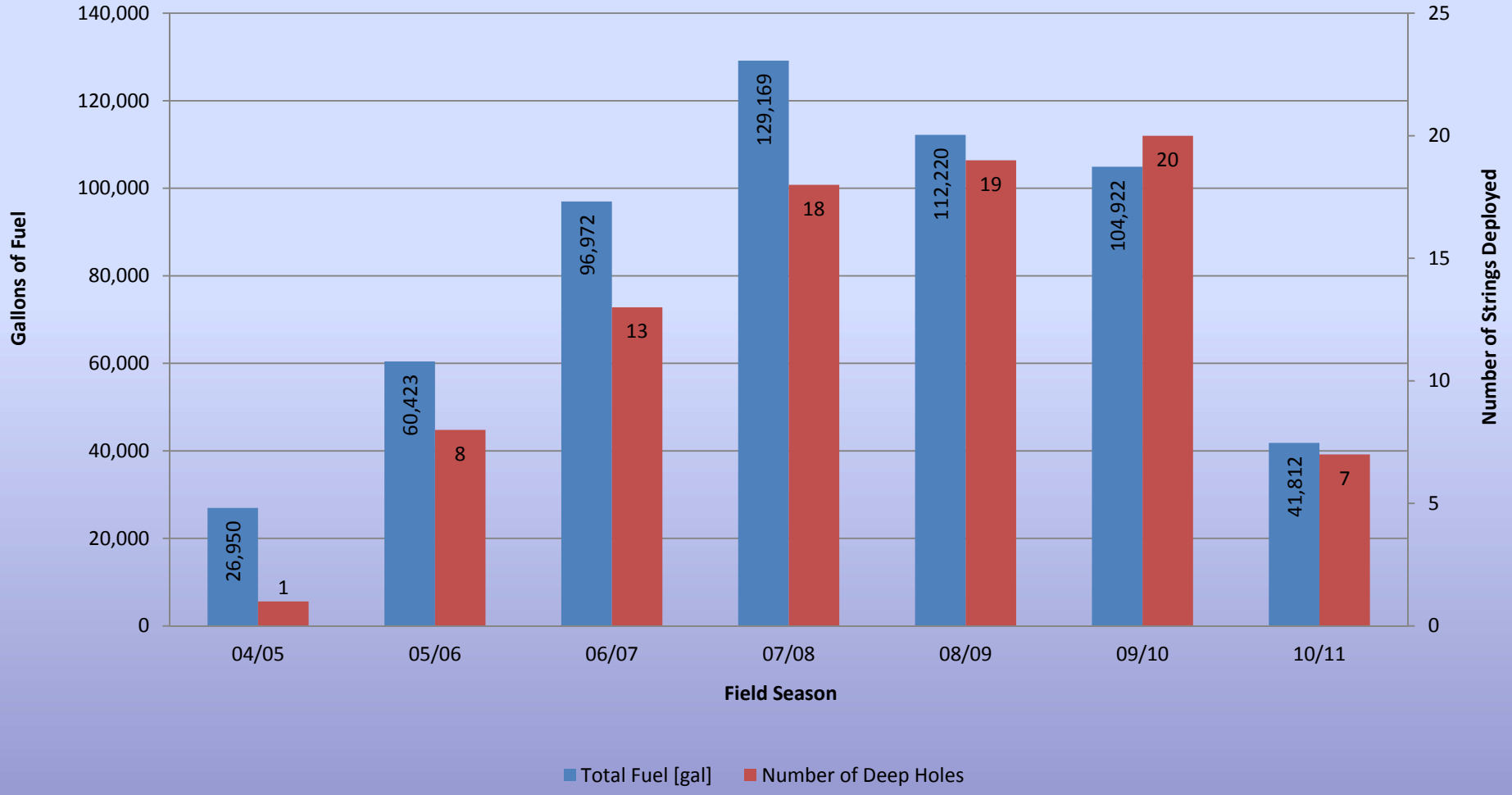
Fuel History

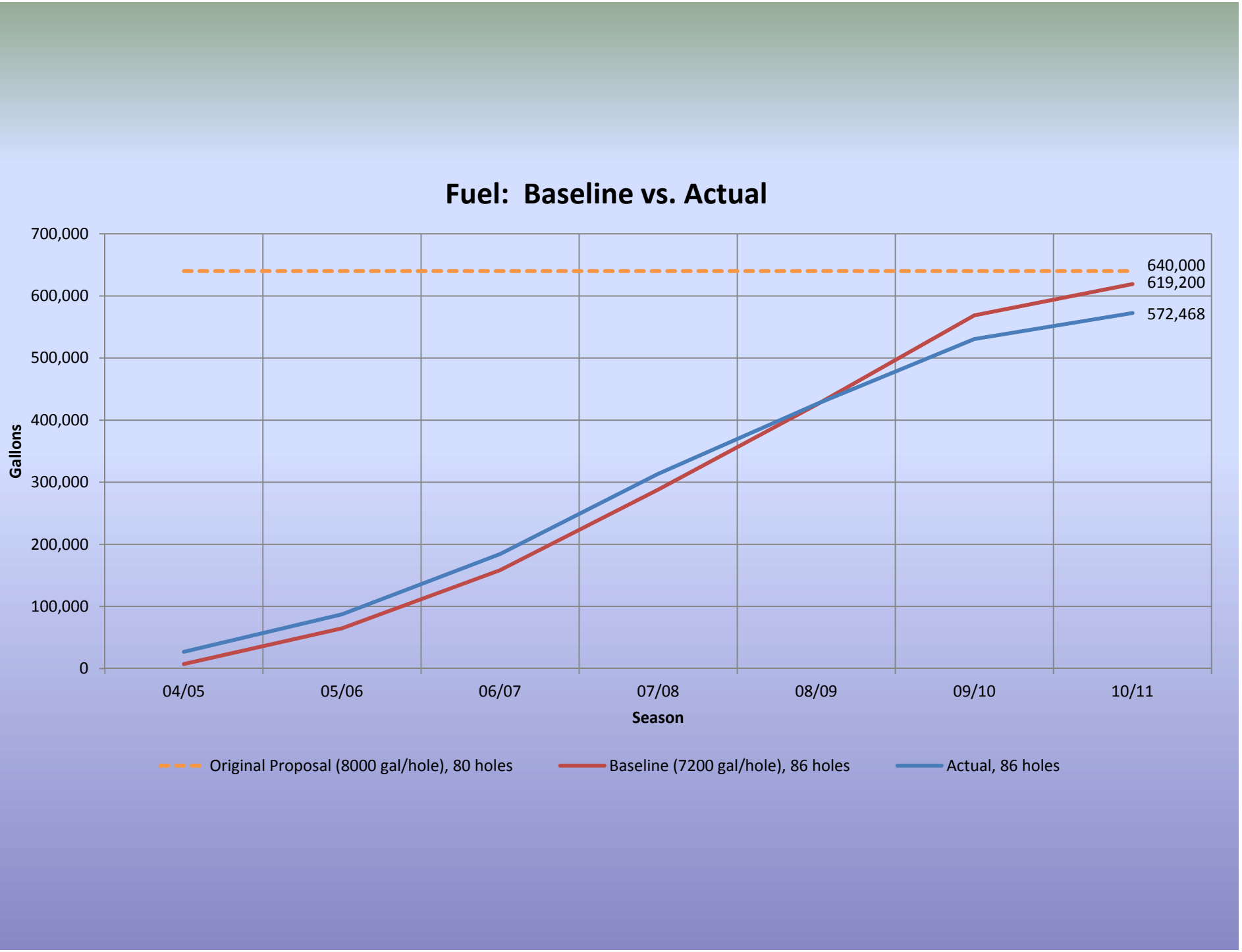
	04-05	05-06	06-07	07-08	08-09	09-10	10-11	SUM	AVERAGE
Number of Deep Holes	1	8	13	18	19	20	7	86	
Number of IFD Holes	1	8	14	22	20	25	0	90	
Total Fuel [gal]	26,950	60,423	96,972	129,169	112,220	104,922	41,812	572,467	
Accumulated Fuel [gal]	26,950	87,373	184,345	313,514	425,734	530,656	572,467		
Macro Fuel-Per-Hole [gal]	26,950	7,553	7,459	7,176	5,906	5,246	5,973		6,657 **
Deep Drilling [gal]	11,989	41,590	73,479	93,243	86,769	79,672	27,904	414,646	
Per-Hole [gal/hole]	-	5,302	5,681	5,229	4,567	3,984	3,986		4,791
Ave Rate [gal/hr]	-	-	-	-	128	130	128		128
IFD Drilling [gal]	-	1,433	5,217	6,153	4,821	5,106	-	22,730	
Per-Hole [gal/hole]	-	355	474	293	243	204	-		314
Deep + IFD Total [gal]	11,989	43,023	78,696	99,396	91,590	84,778	27,904		
Per-Hole, Deep + IFD [gal/hole]	7,164	5,652	6,155	5,522	4,810	4,188	-		5,582
Base [gal]	14,961	17,400	18,276	29,773	20,630	20,144	13,907	135,092	
Startup [gal]	-	-	-	-	8,182	8,841	5,966		7,663
Shutdown [gal]	-	-	-	-	1,055	1,748	5,362		2,722
Other [gal]	-	-	-	-	1,801	1,168	564		1,178
Idle [gal]	-	-	-	-	9,593	8,387	2,015		6,665
Ave Idle Rate [gal/hr]	-	-	-	-	19	16	15		17
Base-Per-Hole [gal]	14,961	2,175	1,406	1,654	1,086	1,007	1,987		3,468
Error, RPSC to IceCube Records [%]	-	-	-9.00%	1.50%	-1.40%	0.06%	0.84%		-1.60%

"-" = data not found or not available

** Calculated from (Total Fuel ÷ Number of Deep Holes)

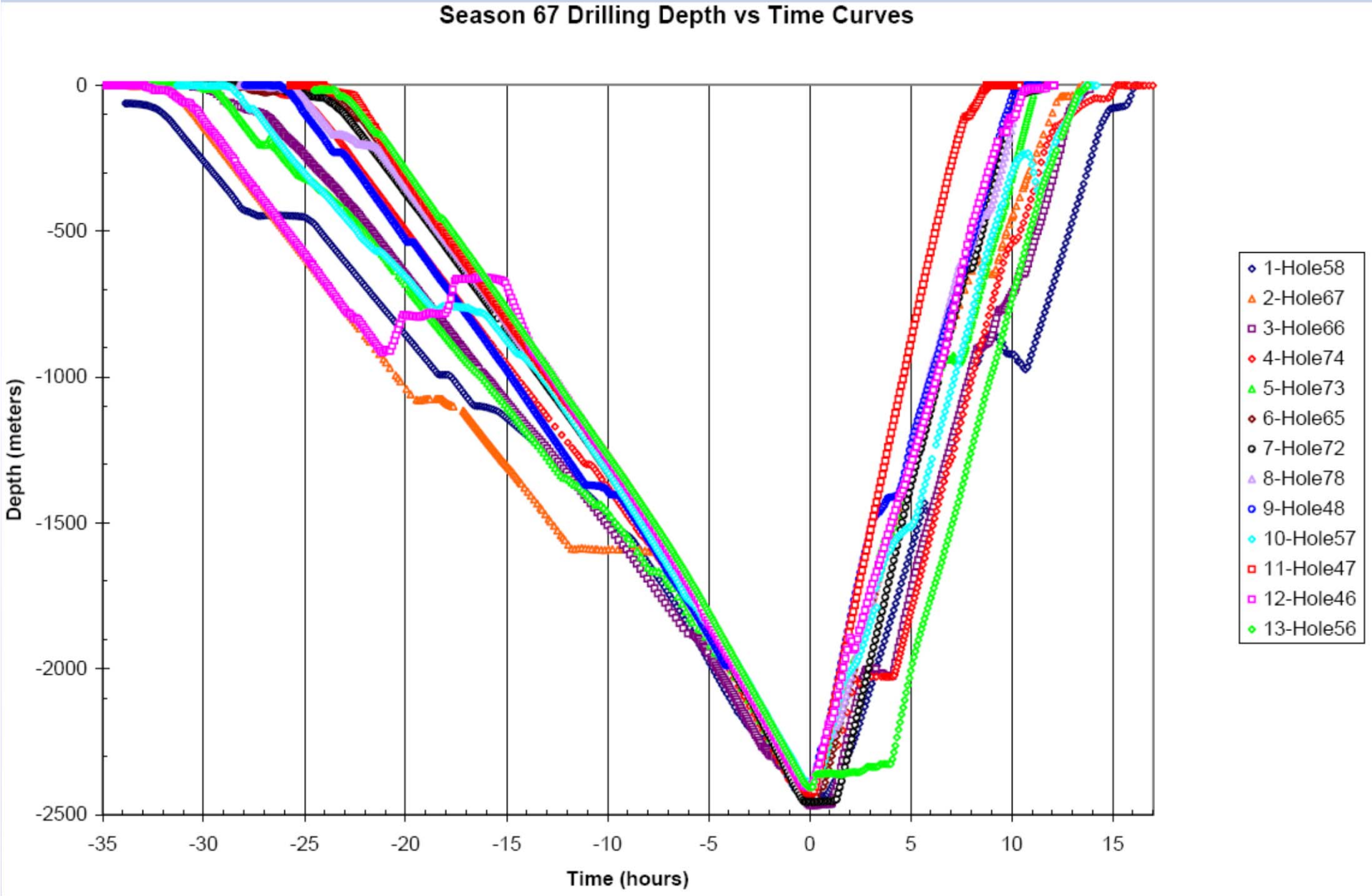
IceCube Seasonal Fuel Usage




Fuel: Baseline vs. Actual
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
Gallons
640,000
619,200
572,468
04/05
05/06
06/07
07/08
08/09
09/10
10/11
Season
Original Proposal (8000 gal/hole), 80 holes
Baseline (7200 gal/hole), 86 holes
Actual, 86 holes


EXIT
TOS 1
2

Performance: 06-07



Performance: 09-10